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PUSH-PULL TEST FOR *IN SITU* DETERMINATION OF MICROBIAL METABOLIC ACTIVITIES: DENITRIFICATION AND METHANOGENESIS

by

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submitted to
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the requirements for the
degree of

Master of Science

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Abstract

Quantitative information on subsurface microbial processes is needed for many applications, but information obtained by existing methods can be difficult to interpret. The goal of this project was to develop a single well, "push-pull" test for the determination of *in situ* microbial metabolic activities. The method consists of an injection of a test solution into an existing monitoring well followed by the extraction of the groundwater/test solution mixture from the same well. The test solution consists of a tracer and one or more reactive solutes selected to investigate the activity of a specific microbial system. During the extraction phase, the concentrations of all components of the test solution and potential reaction products are measured and used to develop breakthrough curves. A series of tests were used to investigate the processes of denitrification and methanogenesis by injecting solutions with nitrate, nitrite, or dissolved hydrogen gas in a petroleum contaminated, anaerobic zone of an unconfined, alluvial aquifer and in an uncontaminated, aerobic zone of the same aquifer located directly upgradient of the contaminated zone. Nitrate and nitrite injections yielded utilization rates that were approximately 2.5 times greater in the contaminated zone (than in the uncontaminated zone) where 80% of the injected nitrate mass and 90% of the injected nitrite mass were utilized. During the nitrate injection tests, trace amounts of produced nitrite were detected. The hydrogen injection test resulted in a 60% loss of hydrogen with no detectable methane production in the contaminated well. The "push-pull" field procedure developed in this project was shown to be capable of determining and quantifying microbial metabolic activity *in situ*.

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PUSH-PULL TEST FOR *IN SITU* DETERMINATION OF MICROBIAL METABOLIC ACTIVITIES: DENITRIFICATION AND METHANOGENESIS.

Introduction

Background

There is a growing need for the ability to determine microbial activity in the field. This information is needed for a variety of applications. It is necessary for quantifying rates of intrinsic bioremediation (natural attenuation) of groundwater contaminants. It can also provide site-specific values for microbial activities used in designing enhanced *in situ* bioremediation systems. Field determination is also a powerful tool for comparing the effectiveness of proposed alternate remediation strategies. In a broad sense, it also improves our understanding of microbially mediated reactions in the subsurface at contaminated and pristine sites.

Information on *in situ* microbial activity obtained using existing methods can be inaccurate, difficult to interpret, and time intensive. Several methods which are commonly used are: rate calculations based on monitoring well data; batch, column and microcosm reactor studies; direct observation, cell counts, and biochemical markers; analysis of geochemistry data; and molecular methods. Several problems limit the usefulness of these existing methods. Several methods require core material which may not be readily available or can be costly to obtain. Another major limitation is that determining field conditions and reproducing them in an artificial laboratory environment is difficult and never completely achieved. Small sample volumes used in these methods may not provide an adequate representation of actual field conditions and often a mass

balance can not be determined. Sample collection procedures can also disturb actual conditions and contamination often occurs during sampling. Selective growth and enrichment techniques also are of limited value as they do not provide an overall picture of competing processes in a complex consortium of microbial species.

Objective

The overall objective of this research was to develop a simple yet effective field procedure that allows microbial metabolic activity to be measured *in situ*. This resulted in the development of a single well, push-pull method which has applications for both aerobic and anaerobic processes. In a push-pull test a solution is injected into a groundwater aquifer through a well and then extracted from the same well. The test allows for various electron acceptors or donors to be introduced to the subsurface in an ionic form or as a dissolved gas. In most cases, the test can be performed in a single day in most monitoring wells. The push-pull procedure also allows for a rigorous mass balance and calculation of reaction rates.

Microbial Processes

Denitrification

Denitrification is an anaerobic respiration process where nitrate (NO_3^{-1}) is sequentially reduced to gaseous forms such as nitrous oxide (N_2O) and nitrogen gas (N_2). The denitrification process is mediated by facultative aerobic bacteria such as *Pseudomonas* which in the absence of oxygen will use nitrate or other inorganics as electron acceptors (Brock et al., 1994).

The nitrate is first reduced to nitrite (NO_2^{-1}). In this reaction the nitrogen is taken from a +5 oxidation state to +3. Nitrate acts as an electron acceptor and the transformation is characterized by the half reaction and the free energy of formation ($\Delta G^{o'}$):

$$0.5\ NO_3^{-1} + H^+ + e^- \rightarrow 0.5\ NO_2^{-1} + 0.5\ H_2O$$

$$\Delta G^{o'} = -41.7\ KJ/\ e^-\text{-mole}$$

When coupled with an organic compound as the electron donor a generalized equation would be of the form:

$$\text{Carbon Source} + NO_3^{-1} \rightarrow NO_2^{-1} + CO_2 + H_2O$$

The nitrite is then reduced predominantly to nitrous oxide or nitrogen gas which have nitrogen oxidation states of +1, and 0, respectively. Nitrous oxide can be produced directly from nitrite or with nitric oxide (oxidation state +2) as an intermediate. The electron acceptor half reaction in which nitrite is transformed to nitrous oxide is:

$$0.5\ NO_2^{-1} + 1.5\ H^+ + e^- \rightarrow 0.25\ N_2O + 0.75\ H_2O$$

$$\Delta G^{o'} = -73.5\ KJ/\ e^-\text{-mole}$$

A complete reaction can be generalized by:

$$\text{Carbon Source} + NO_2^{-1} \rightarrow N_2O + CO_2 + H_2O$$

Nitrous oxide can be further reduced to nitrogen gas:

$$0.5\ N_2O + H^+ + e^- \rightarrow 0.5\ N_2 + 0.5\ H_2O$$

$$\Delta G^{o'} = -130.9\ KJ/\ e^-\text{-mole}$$

Methanogenesis

Methanogenesis is an anaerobic respiration where methane is formed as a product. This process is mediated by a highly specialized group of obligate anaerobes called methanogens. The most prevalent methanogenic process involves hydrogen gas as the electron donor and carbon dioxide as the electron acceptor:

$$4\ H_2 + CO_2 \rightarrow CH_4 + 2\ H_2O$$

$$\Delta G^{o'} = -130.7\ KJ/\ reaction$$

In this reaction carbon is reduced from an oxidation state of +4 to -4 and hydrogen is oxidized from an oxidation state of 0 to +1 (Brock et al., 1994).

Hydrogen is available through a process called interspecies hydrogen transfer. In this process, energetically unfavorable reactions which convert higher carbon forms to acetate and also produce hydrogen are coupled with the above methanogenic reaction to yield an overall energetically favorable reaction.

Methods and Materials

Overview

The field experiments were conducted at a petroleum contaminated site in Corvallis, Oregon. Two existing monitoring wells were used. The first well is located in an uncontaminated, aerobic zone directly upgradient of the contaminated zone. The second well is located in the contaminated, anaerobic zone of the aquifer. The experiments consisted of an injection phase and an extraction phase. The injection was made using a measured quantity of tap water with a bromide tracer and various electron acceptors or donors. The extraction was accomplished using a submersible pump. During the

extraction, the concentrations of injected solution components and possible reaction products were measured. Concentration breakthrough curves were plotted. Mass balances and utilization rates were computed.

Pretest Pumping

Prior to beginning the injection phase the initial water level was measured using a contact meter (Model L 50M, Leupold and Stevens, Inc., Beaverton, Oregon). Approximately 3 casing volumes (volume of the saturated portion of the well and the pore space of the sand pack) were extracted from the well to obtain an initial groundwater sample. The sample was used to calibrate test equipment, measure background concentrations of solution components, and determine the initial groundwater temperature.

Injection Phase

The injection consisted of 3 casing volumes of a prepared injection solution followed by 1 casing volume of tap water with no added solutes ("clean water"). In all tests, the clean water was sparged with nitrogen gas to remove dissolved oxygen. The injection solution was prepared using tap water and potassium bromide to establish a 100 mg/l (1.25 mM) bromide tracer solution. In the nitrate tests, sodium nitrate ($NaNO_3$) was added to the injection solution to prepare a 5 mg/l NO_3^{-1}-N (0.36 mM NO_3^{-1}-N) solution. The injection solution was sparged with compressed nitrogen gas to remove oxygen. In the nitrite tests, sodium nitrite ($NaNO_2$) was used to prepare a 0.5 mg/l NO_2^{-1}-N (0.14 mM NO_2^{-1}-N) solution and the solution was sparged with nitrogen gas. In the hydrogen

tests, the injection solution was first sparged with compressed nitrogen gas to remove dissolved oxygen and then sparged with compressed hydrogen gas to achieve hydrogen saturation.

The injection system is illustrated in Figure 1. The injection was accomplished using a two stage gas transfer system. Initial sparging occurred in a 125 gallon storage tank. The solution was then pumped to a small gas adsorption column on the well head. Once entering the column the solution was distributed over a ceramic ring packing material. The compressed gas entered the column below the packing material. A portion of the gas then traveled through the packing material, countercurrent to the water flow to provide effective gas transfer. After passing through the packing material the injection solution traveled through a hose to the bottom of the well accompanied by a small portion of gas. The gas traveling to the bottom of the well served to ensure that high dissolved concentrations were maintained during injection and also formed bubbles which serve to vertically mix the injection solution within the well casing.

The injection rate was selected to keep water table mounding (a vertical rise in the water table elevation) less than 20 centimeters (0.65 feet). Injection rates ranged from 0.75 liters per minute (0.2 gallons per minute (gpm)) to 2 liters per minute (0.5 gpm).

Extraction Phase

The extraction system is shown in Figure 2. The extraction was accomplished using a portable sampling system (REEL E-Z Model 200, Instrumentation Northwest, Inc., Redmond, Washington) which includes an electrical submersible pump (MP1 Model

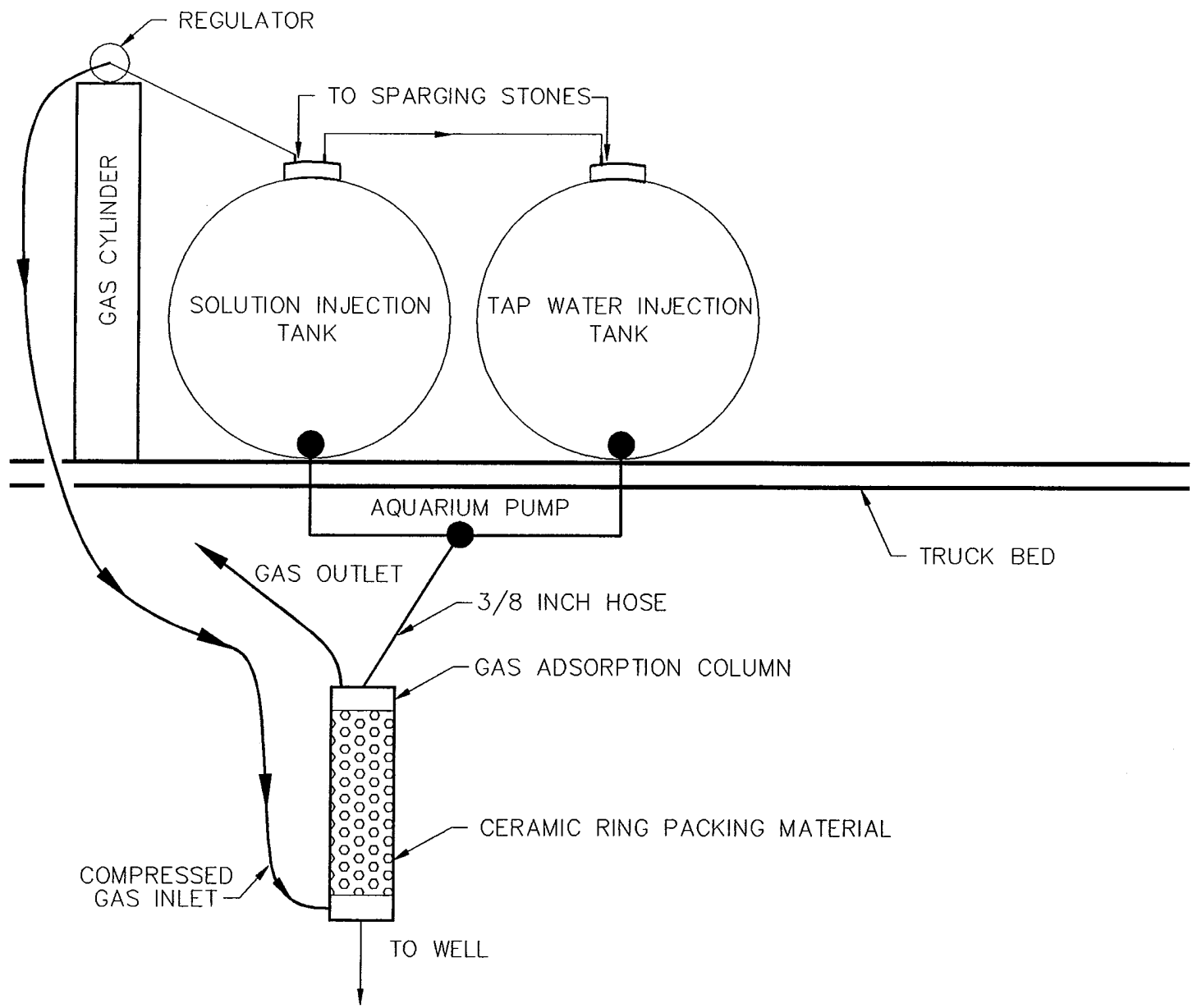


FIGURE 1
INJECTION SYSTEM

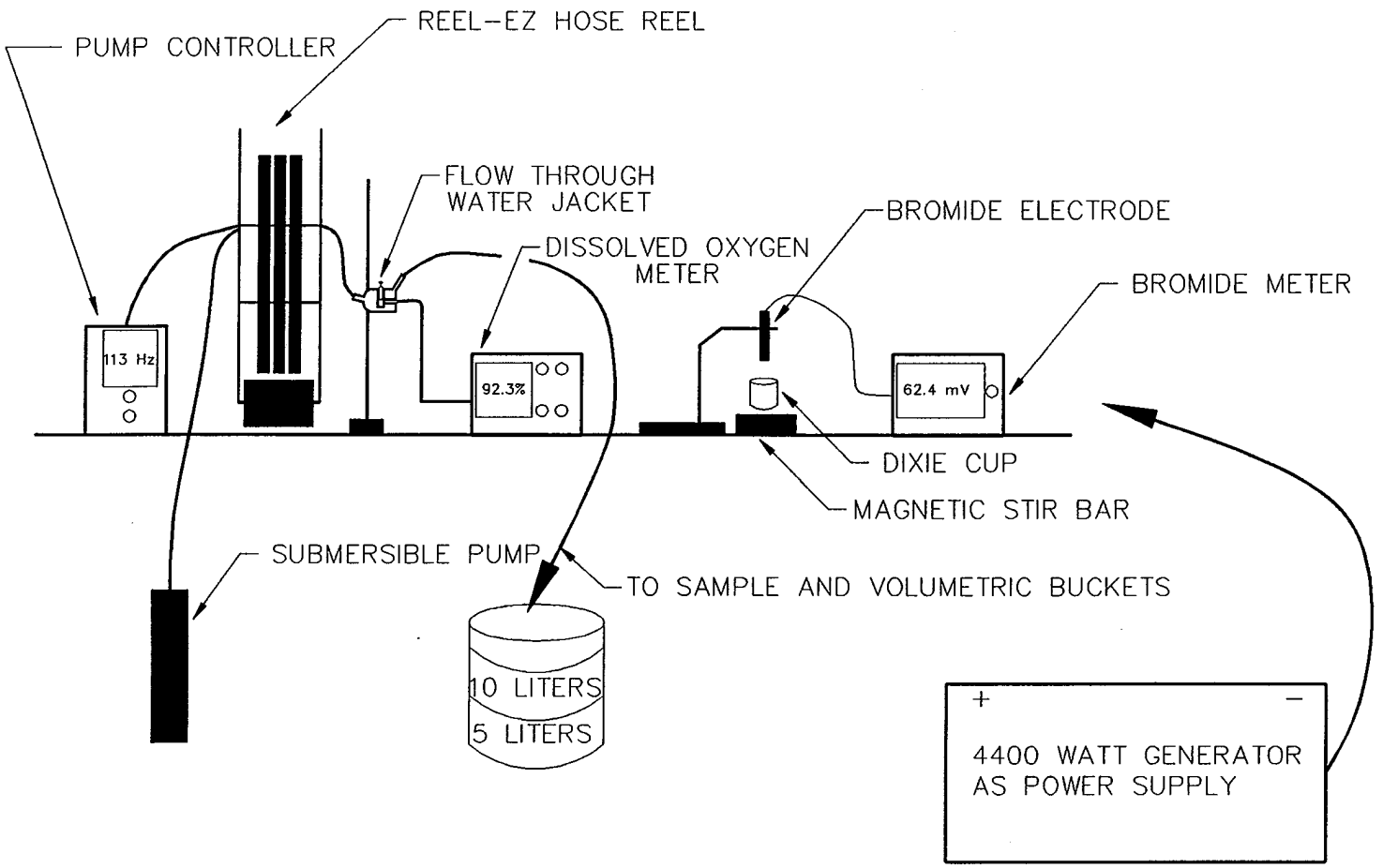


FIGURE 2
EXTRACTION AND MEASUREMENT SYSTEM

1A106003, Grundfos, Dierikon, Switzerland) controlled by a variable frequency inverter (INVERTRON BMI/MP1-115V Model 1A9915, Grundfos, Dierikon, Switzerland).

The extraction rate was selected to keep drawdown (vertical decline in the water table elevation) less than 20 centimeters (0.65 feet). Extraction rates ranged from 0.75 liters per minute (0.2 gpm) to 2 liters per minute (0.5 gpm).

The discharge from the sampling system was directed into 10 liter (2.6 gallon) volumetric containers. Samples were taken every 5 liters (1.3 gallons) or 10 liters (2.6 gallons) of extraction and elapsed time from the beginning of the extraction phase was recorded to establish the flow rate. The total extracted volume was approximately three times the volume of the total injected volume.

Sample Analysis

Bromide

Bromide concentrations were measured by a combination glass body bromide electrode (Model 27502-05, Cole-Parmer Instrument Company, Niles, Illinois). The bromide electrode was connected to an ion-specific meter (Accumet Model 25, Denver Instrument Company, Arvada, Colorado) which displayed the probe potential in millivolts. Millivolt readings were converted to concentrations using standard curves developed in the field prior to the start of each experiment. The standard curve consisted of eight data points ranging from 5 mg/l (0.06 mM) to 120 mg/l (1.5 mM) with an average correlation coefficient in excess of 0.999.

Dissolved Hydrogen Gas

Dissolved hydrogen concentrations were determined using amperimetric methods as described in Hanus *et al.* (1980) using a Clark type polarigraphic oxygen probe (Model 5331, Yellow Springs Instrument Co., Yellow Springs, OH). The probe was conditioned using an electrode preconditioning oscillator and connected to a modified dissolved oxygen meter (YSI Model 5300 Biological Oxygen Monitor, Yellow Springs Instrument Co., Yellow Springs, OH) as described in Sweet et al. (1980). The meter displayed the dissolved hydrogen concentration in percent of saturation. Measurements were conducted in a water jacketed glass chamber using the extraction pump discharge as the temperature control fluid.

Nitrate

Nitrate-nitrogen concentrations in the range of 0 to 1 mg/l (0.07 mM) and 1 (0.07 mM) to 5 mg/l (0.36 mM) expressed as NO_3^{-1}-N, were determined using CHEMets® self filling ampoules for colorimetric analysis (Cat. No. K-6902, CHEMetrics, Inc., Calverton, Virginia). The method is described in APHA (1992), ASTM (1993), and EPA (1983).

Nitrite

Nitrite-nitrogen concentrations in the range of 0 to 0.4 mg/l (0.03mM) and 0.4 (0.03 mM) to 2 mg/l (0.14 mM) expressed as NO_2^{-1}-N, were determined using CHEMets® self filling ampoules for colorimetric analysis (Cat. No. K-7002, CHEMetrics, Inc., Calverton, Virginia). The method is referenced in APHA (1980).

Methane

Ten milliliters groundwater samples were taken from the extraction pump discharge using a syringe and injected into a 40 mL serum bottle. After allowing 24 hours for equilibration with the gas phase, a 100 µL headspace sample was analyzed using a gas chromatograph (Model GC-8A, Shimadzu Instrumentation, Inc., Columbia, Maryland) with a 1 meter, 0.125 inch inside diameter stainless steel column and a flame ionization detector.

Dissolved Oxygen

Dissolved oxygen concentrations in the range of 0 to 100 µg/l (3 µM) and 0 to 1 mg/l (0.03 mM) were determined by using CHEMets® self filling ampoules for colorimetric analysis (Cat. No. K-7599 and Cat. No. K-7501, CHEMetrics, Inc., Calverton, Virginia). The method is referenced in ASTM (1984).

Field Logistics

A one ton flatbed truck with stake sides was used to transport equipment and served as a work platform. Power was supplied for electrical equipment by a 4400 watt, 8 horsepower gasoline powered generator (Model LR4400, Homelite, Charlotte, North Carolina). Three 125 gallon polyolefin tanks (TK125X30, Snyder Industries, Inc., Lincoln, NE) were used for holding injection solutions and extracted groundwater. A 12 inch dumpy level (Model 2040, Seiler Instrument and Manufacturing Co., St. Louis, MO), a Philadelphia rod (Type C, Keuffel and Esser Co.) and a contact meter were used to determine the elevation of the well heads.

Site Description

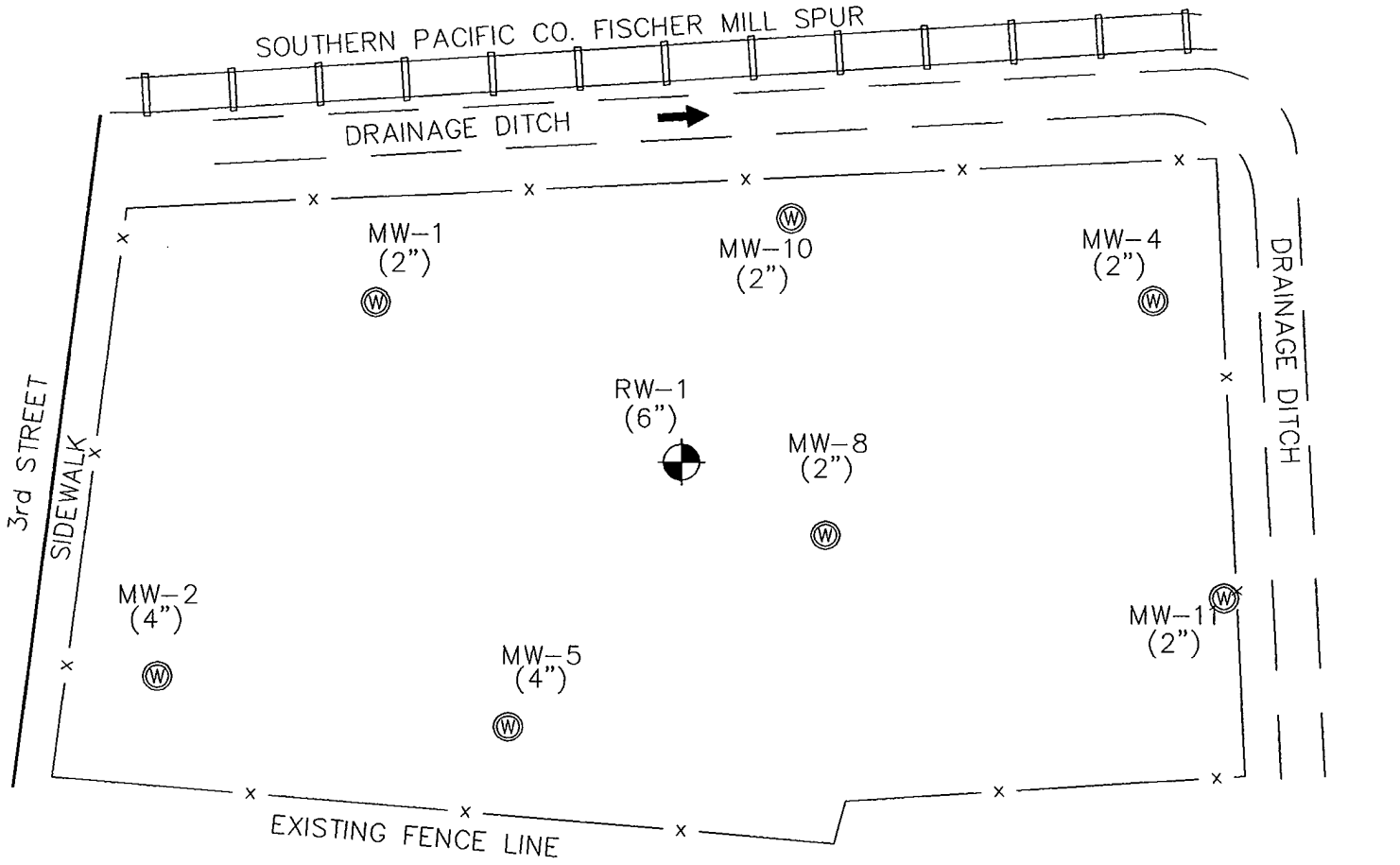
History, Location, and Nature of Contamination

The test site is a former Chevron Bulk Terminal Transfer Station, # 100-1761, located at 1225 SE Third Street, in Corvallis, Oregon. The site was contaminated with petroleum hydrocarbons from leaking underground storage tanks and surface spills during transfer operations. A total of fourteen monitoring wells and one recovery well were installed for monitoring and remediation. The monitoring wells were sampled for BTEX (Benzene, Toluene, Ethylbenzene, and Xylenes) contamination over a five year period. At the conclusion of the remediation phase, several of the wells were abandoned. The locations of the remaining active monitoring wells are shown on Figure 3.

Test Well Descriptions

The existing wells used for this study consist of an upgradient well, MW-2, and a downgradient well, MW-4. A water table elevation contour map with the locations of MW-2 and MW-4 superimposed is shown in Figure 4. Groundwater flow at the site is towards the Northeast at approximately one foot per day (0.3 meters per day).

The upgradient well, MW-2, is a 4 inch (10.2 centimeter) diameter monitoring well approximately 21 feet (6.4 meters) deep, fully screened across a saturated thickness of approximately 3.3 feet (1 meter). The downgradient well, MW-4, is a 2 inch (5.1 centimeters) diameter monitoring well approximately 30.5 feet deep (9.3 meters) with a 15 foot (4.6 meters) screened interval, and average saturated thickness of approximately



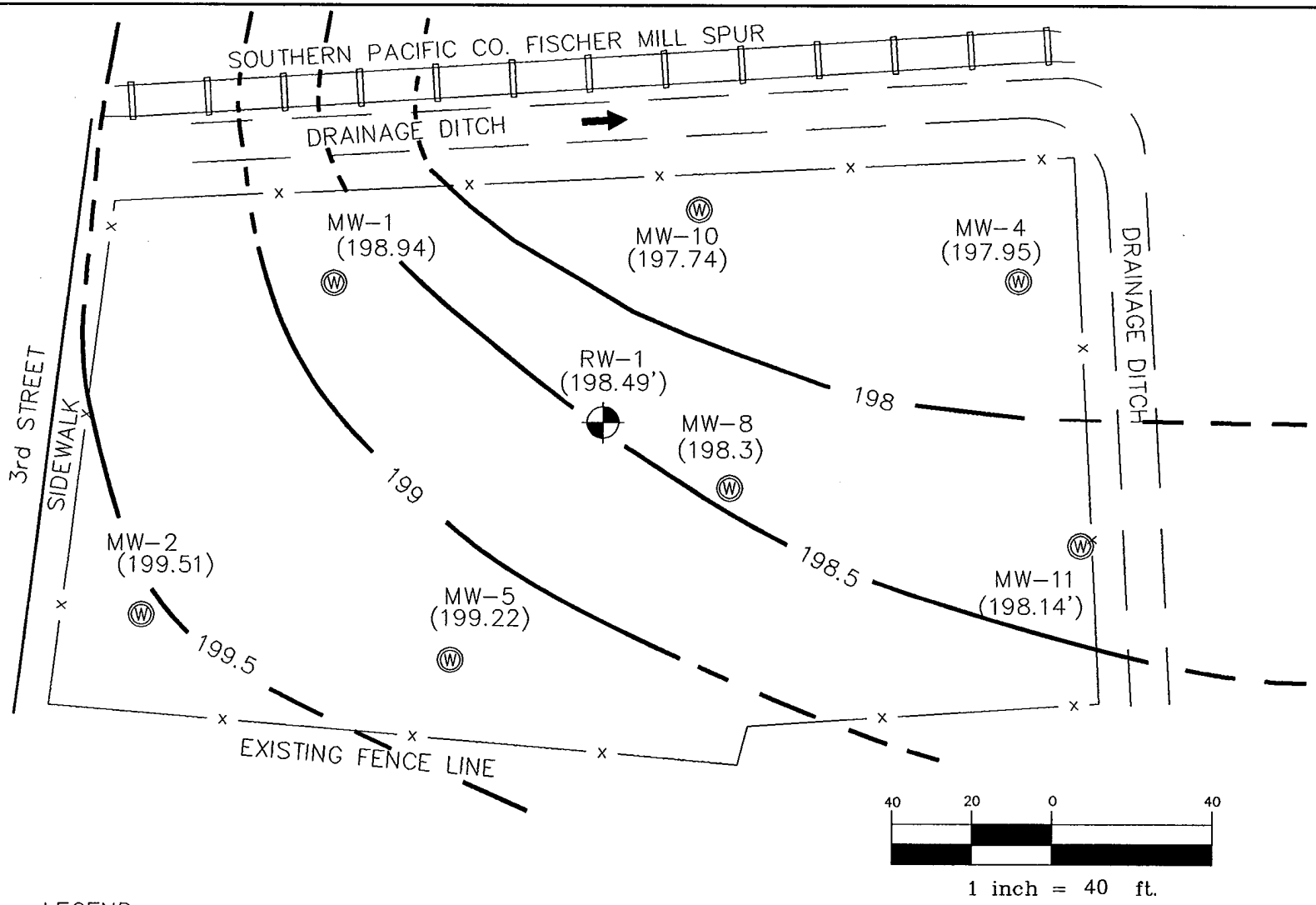
LEGEND

Ⓦ MONITORING WELL LOCATION

RECOVERY WELL LOCATION

(4") WELL DIAMETER (in)

FIGURE 3
MONITORING WELL LOCATIONS



LEGEND

- MONITORING WELL LOCATION
- RECOVERY WELL LOCATION
- (199.99) WATER ELEVATION (MSL)
- 199.5 APPROXIMATE WATER TABLE CONTOUR AS OF 09/07/95

FIGURE 4
WATER TABLE CONTOUR MAP

11 feet (3.4 meters). In general, the stratigraphy consists of a clayey silt overlying interbedded sands and gravels. The boring log for MW-4 is included as Appendix I. The boring log for MW-2 is not available.

Nature Of Contamination and Chemistry of Test Wells

MW-2 and MW-4 were tested periodically for BTEX contamination from August of 1989 to August of 1994. The testing dates and concentration ranges encountered are summarized in Table 1. Initial groundwater concentrations of injection solution components is given in Table 2.

Results and Discussion

Nitrate Injection Tests

Appendix II is a chronological record of all tests performed. Five nitrate injection tests were conducted; two in the upgradient well, MW-2 and three in the downgradient well, MW-4. The field data and calculations for the five tests are included as Appendix III. Table 3 is a summary of the results of two tests. The first test was conducted on 18 August 1995 in MW-2. The second test was conducted on 13 September 1995 in MW-4. Breakthrough curves for the tests performed in MW-2 and MW-4 are given as Figure 5 and Figure 6, respectively. The breakthrough curves are a plot of the relative concentration (C) measured divided by the injection concentration (Co) of each component versus the volume extracted divided by the total volume injected (Extracted/Injected).

In Table 3, the mass injected for bromide and nitrate were determined by the test method. The injected mass of nitrite reported is an assumed value based on the complete

Table 1: Summary of Sampling for MW-2 AND MW-4

Location	Date	Benzene (ppb)	Toluene (ppb)	Ethylbenzene (ppb)	Xylene (ppb)
MW-2	Aug-89	ND	ND	ND	2
	Dec-89	ND	ND	3	ND
	Apr-90	ND	ND	ND	ND
	Oct-90	ND	ND	ND	ND
	Dec-90	ND	ND	ND	ND
	Feb-91	ND	ND	ND	ND
	Sep-91	ND	ND	ND	ND
	Sep-92	*	*	*	*
	Sep-93	<0.5	<0.5	<0.5	<0.5
	Nov-93	<0.5	<0.5	<0.5	<0.5
	Feb-94	<0.5	<0.5	<0.5	<0.5
	May-94	<0.5	<0.5	<0.5	<0.5
	Aug-94	<0.5	<0.5	<0.5	<0.5
MW-4	Aug-89	2	ND	2	ND
	Dec-89	0.4	0.5	0.2	0.1
	Apr-90	1.5	0.4	0.8	0.8
	Oct-90	ND	ND	ND	ND
	Dec-90	0.3	ND	0.3	0.2
	Feb-91	ND	ND	ND	ND
	Sep-91	ND	ND	ND	ND
	Sep-92	*	*	*	*
	Sep-93	1.2	<0.5	<0.5	<0.5
	Nov-93	*	*	*	*
	Feb-94	1.1	<0.5	<0.5	<0.5
	May-94	1.0	<0.5	<0.5	<0.5
	Aug-94	*	*	*	*

* =NOT MEASURED, SAMPLED OR ANALYZED

ND =NOT DETECTED ABOVE REPORTING LIMIT AS REPORTED BY OTHERS

BTEX ANALYSIS BY EPA METHOD 8020

Table 2: Initial Groundwater Concentrations

Component	MW-2 *mg/l*	MW-4 *mg/l*
Oxygen	0.80	0.01
Nitrate-N	0.10	0.00
Nitrite-N	0.02	0.00
Hydrogen	0.02	0.03
Methane	ND*	0.067
Sulfate	16	0

* ND = Not determined.

Table 3: Nitrate Injection Test Results

Well Date	MW-2 18 August 1995				MW-4 13 September 1995			
	Volume *Liters*		Time *Minutes*		Volume *Liters*		Time *Minutes*	
Injection Solution Clean Total Extraction	58 30 88 142.5		86 24 110 161		90 35 125 247.5		100 30 130 197	
Component	Injection Concentration *mg/l*	Mass *mg*	Extraction Mass *mg*	Percent Recovery	Injection Concentration *mg/l*	Mass *mg*	Extraction Mass *mg*	Percent Recovery
Bromide	93.57	5445.06	5144.06	93.92%	107.65	9709.13	9671.80	99.62%
Nitrate-N	4.75	275.50	195.00	70.78%	4.50	405.00	84.00	20.74%
Nitrite-N*	N/A	80.50	3.88	4.81%	N/A	321.00	1.00	0.31%
	Utilization Rate *mg/l-min*				Utilization Rate *mg/l-min*			
Nitrate-N Nitrite-N	0.0052 0.0049				0.013 0.012			

* The nitrite injection mass given in this table is equal unrecovered nitrate mass.

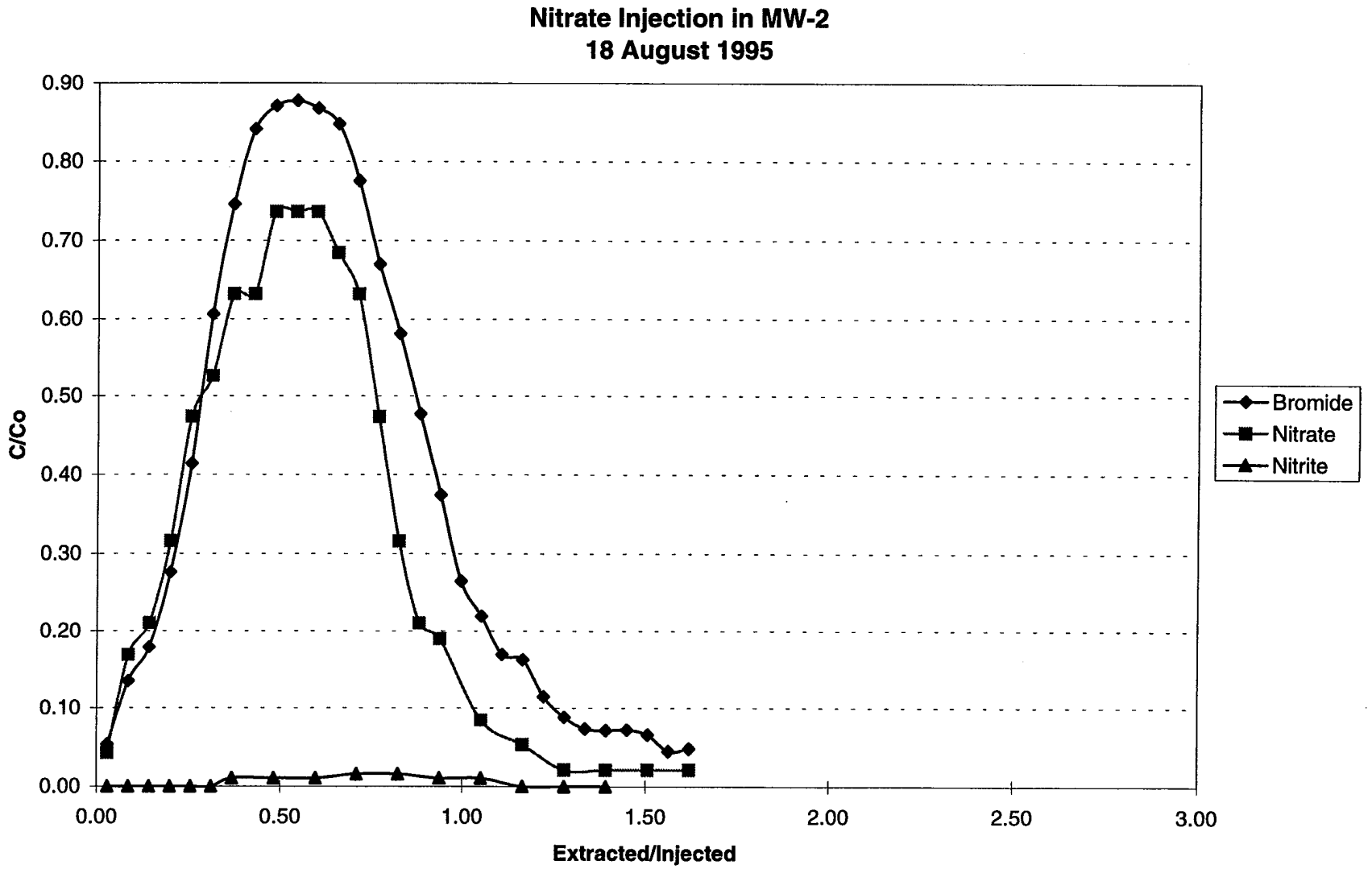


Figure 5: Breakthrough Curve, Nitrate Injection in MW-2, 18 August 1995

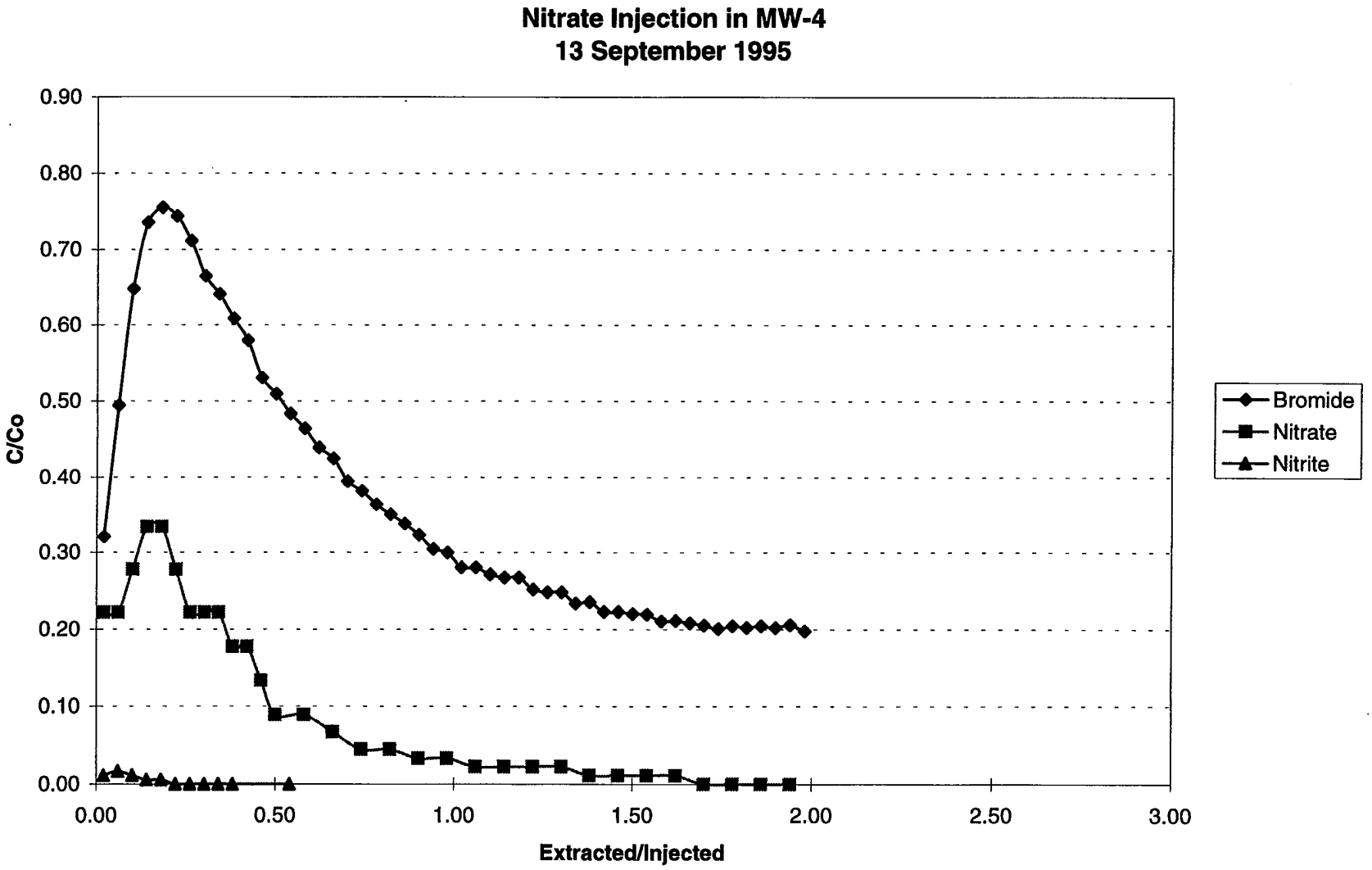


Figure 6: Breakthrough Curve, Nitrate Injection in MW-4, 13 September 1995

conversion of the unrecovered nitrate to nitrite. The utilization rate was computed as the mass injected ($M_{injected}$) minus the mass recovered ($M_{recovered}$) divided by the volume injected ($V_{injected}$) and the time from the beginning of the injection phase to the mass centroid time of the bromide breakthrough curve ($T_{inject\text{-}centroid}$) or:

$$\text{Utilization Rate} = (M_{injected} - M_{recovered})/(T_{inject\text{-}centroid} \times V_{injected})$$

Comparing the results of the two tests, the utilization rates for nitrate were approximately 2.5 times greater for MW-4 than for MW-2. Approximately 71% of the nitrate was recovered in MW-2 compared to 21% in MW-4. Nitrite appeared in both tests in small quantities.

The breakthrough curves for both wells have a similar shape; however, the concentrations towards the end of the experiments tended to decrease more slowly in MW-4 than in MW-2. This effect appeared in all tests that were conducted. A possible explanation for this is that the localized groundwater flow at MW-4 is greater than at MW-2 causing more drift or dilution of the tracer. It is also possible that the difference in saturated thickness between the wells (approximately 3 meters at MW-4 and 1 meter at MW-2) created variances in mixing during injection. Also related to the difference in saturated thickness is the fact that the extraction pump inlet is near the bottom of the well and may not withdraw water uniformly across the saturated thickness.

Nitrite Injection Tests

A single test was run in each well where nitrite was injected into the aquifer. The first test was conducted in MW-2 on 17 August 1995 and the second in MW-4 on 22

August 1995. A summary of the test results is included as Table 4. The field notes and calculations are included as Appendix IV. Figure 7 and Figure 8 are the breakthrough curves.

The utilization rate was computed in the same fashion as described in the nitrate injection test section. MW-4 had a nitrite utilization rate that was 2.6 times greater than that of MW-2. The severe drop on the nitrite breakthrough curve in MW-4 indicates that the majority of the nitrite which reached the aquifer was converted.

Hydrogen Injection Test

A hydrogen test was performed in MW-4 on 6 September 1995. A summary of results is given in Table 5. The field notes and calculations are included as Appendix V. Figure 9 is the breakthrough curve.

In table 5, the injected mass of methane reported is the quantity of methane that would be produced if 100% of the unrecovered hydrogen was converted to methane by methanogenesis. Although only 40% of the hydrogen was recovered, the recovered mass of dissolved methane was extremely low. The shape of the methane breakthrough curve, Figure 9, shows a gradual return to the initial groundwater concentration with no detectable increase due to methane production. This does not mean that methanogenesis did not occur. It is possible that the duration of the test was not long enough for methane production to be detected above the initial groundwater concentration or that the reaction is limited by a lack of carbon dioxide. Due to the high diffusivity of hydrogen it is

Table 4: Nitrite Injection Test Results

Well Date	MW-2 17 August 1995				MW-4 22 August 1995			
	Volume *Liters*		Time *Minutes*		Volume *Liters*		Time *Minutes*	
Injection Solution Clean Total Extraction	 55 30 85 232.5		 39 34 73 203		 84 30 114 242.5		 87 28 114 193	
Component	Injection Concentration *mg/l*	Mass *mg*	Extraction Mass *mg*	Percent Recovery	Injection Concentration *mg/l*	Mass *mg*	Extraction Mass *mg*	Percent Recovery
Bromide Nitrite-N	115.90 0.50	6386.15 27.50	5614.10 19.80	87.91% 72.00%	93.74 0.50	7892.76 42.00	7898.06 3.30	100.07% 7.86%
	Utilization Rate *mg/l-min*				Utilization Rate *mg/l-min*			
Nitrite-N	0.00069				0.0018			

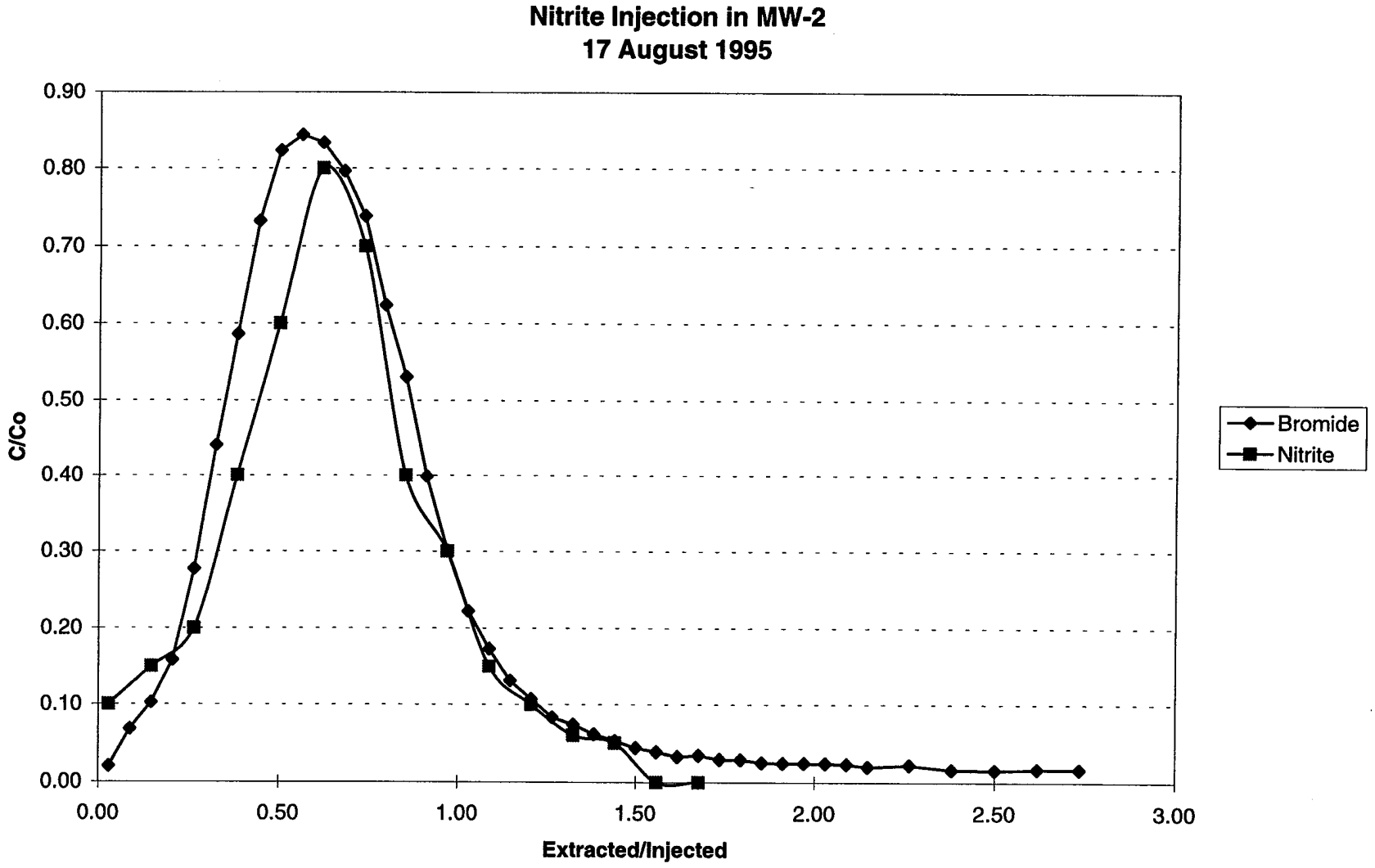


Figure 7: Breakthrough Curve, Nitrite Injection in MW-2, 17 August 1995

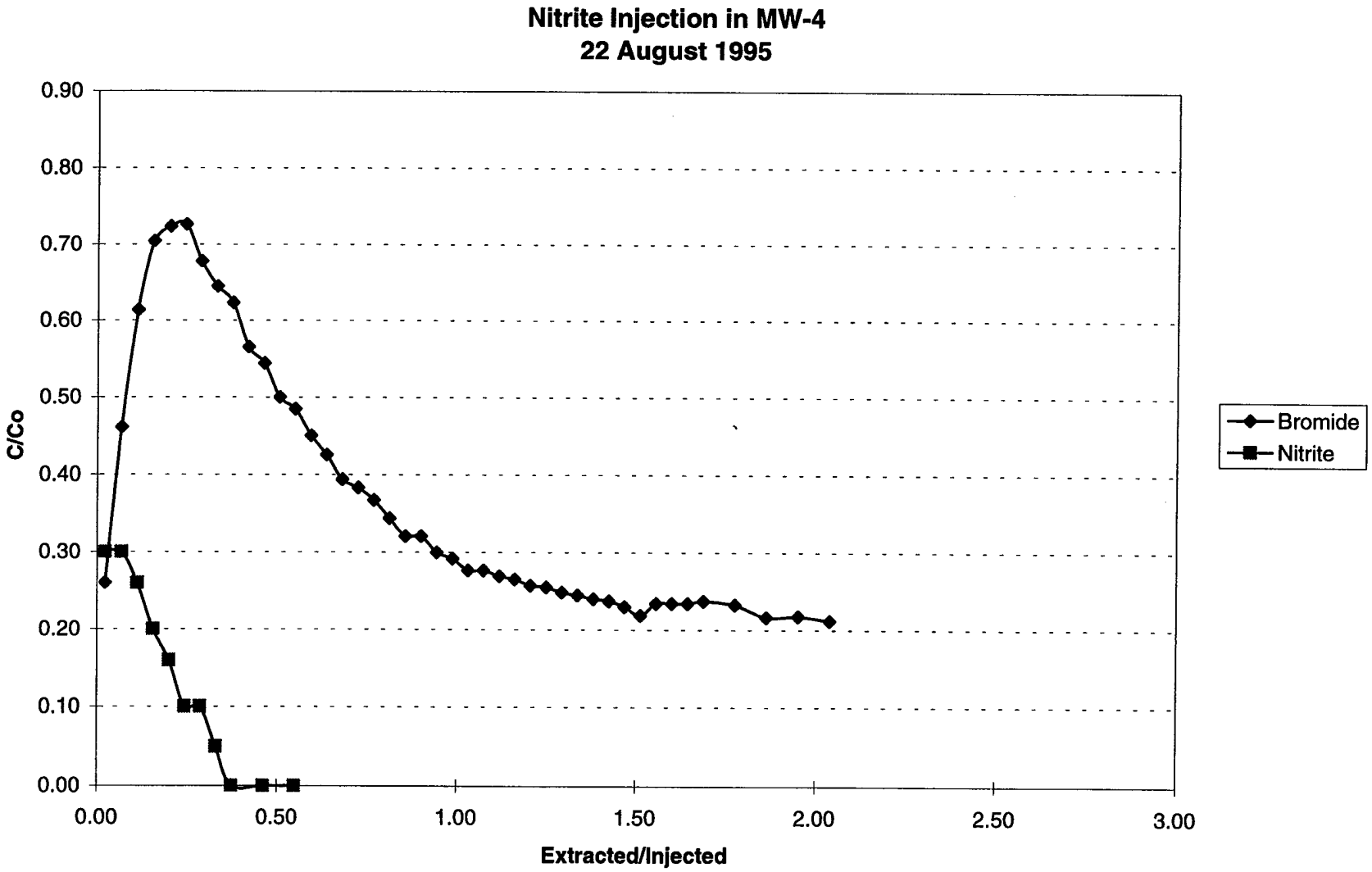


Figure 8: Breakthrough Curve, Nitrite Injection in MW-4, 22 August 1995

Table 5: Hydrogen Injection Test Results

Well Date	MW-4 6 September 1995			
	Volume *Liters*		Time *Minutes*	
Injection Solution Clean Total Extraction	 115 30 145 282.5		 110 31 141 192	
Component	Injection Concentration *mg/l*	Mass *mg*	Extraction Mass *mg*	Percent Recovery
Bromide	88.42	10185.08	9238.47	90.71%
Hydrogen	1.63	187.44	75.80	40.44%
Methane*	N/A	446.59	6.15	1.38%
	Utilization Rate *mg/l-min*			
Hydrogen	0.0036			

* The methane injection mass given in this table is equal to the unrecovered hydrogen mass converted at a 1:4 molar ratio.

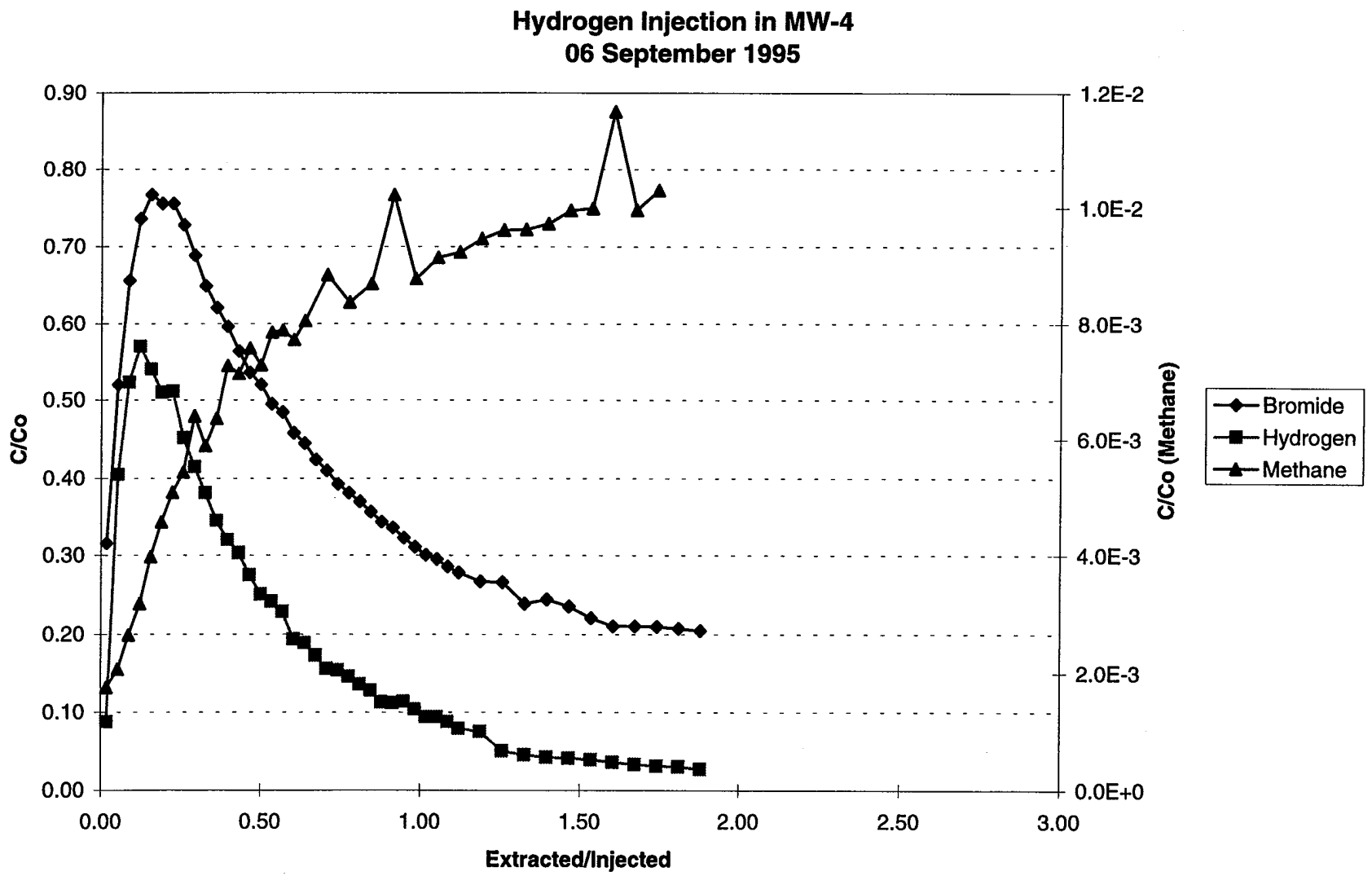


Figure 9: Breakthrough Curve, Hydrogen Injection in MW-4, 6 September 1995

plausible that a large quantity of mass was lost by diffusion through the tubing used for extraction or possibly reacted with another unidentified electron acceptor present in the groundwater.

Due to seasonal fluctuations in the groundwater table a test in MW-2 could not be performed.

Conclusions

The push-pull test developed is a powerful tool for determining microbial metabolic activity. The field tests conducted in this project demonstrated the application of this procedure for denitrification and methanogenesis. All experimental results were well defined and a rigid mass balance was achieved.

The nitrate and nitrite injection tests showed a significant difference in utilization rates between the contaminated and uncontaminated wells. This strongly suggests that denitrification occurred in the downgradient well. The hydrogen injection test showed a significant loss of hydrogen with no detectable methane production. No conclusion can be made as to whether methanogenesis occurred other than it is not as highly favorable a process as denitrification.

Recommendations

In tests where the initial groundwater concentration of a component was significant, the injection of the clean water flush made it impossible to directly distinguish the background concentration from the injected or produced quantity. A conservative tracer (other than that used in the injection solution) added to the clean water flush would allow for the differentiation between groundwater, injection solution, and clean water. This

however adds the complication of testing for another tracer. It may be possible to eliminate the clean water flush and increase the volume of the injected solution. This should yield data which could be interpreted similar to the results of this project.

It became apparent towards the end of the field tests that the gas adsorption column was capable of complete gas transfer without sparging in the 125 gallon tanks. In future tests, gas transfer could be performed effectively in a single stage using the gas adsorption column. This will not only simplify the procedure but will substantially decrease the amount of compressed gas required.

Acknowledgments

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Appendix I

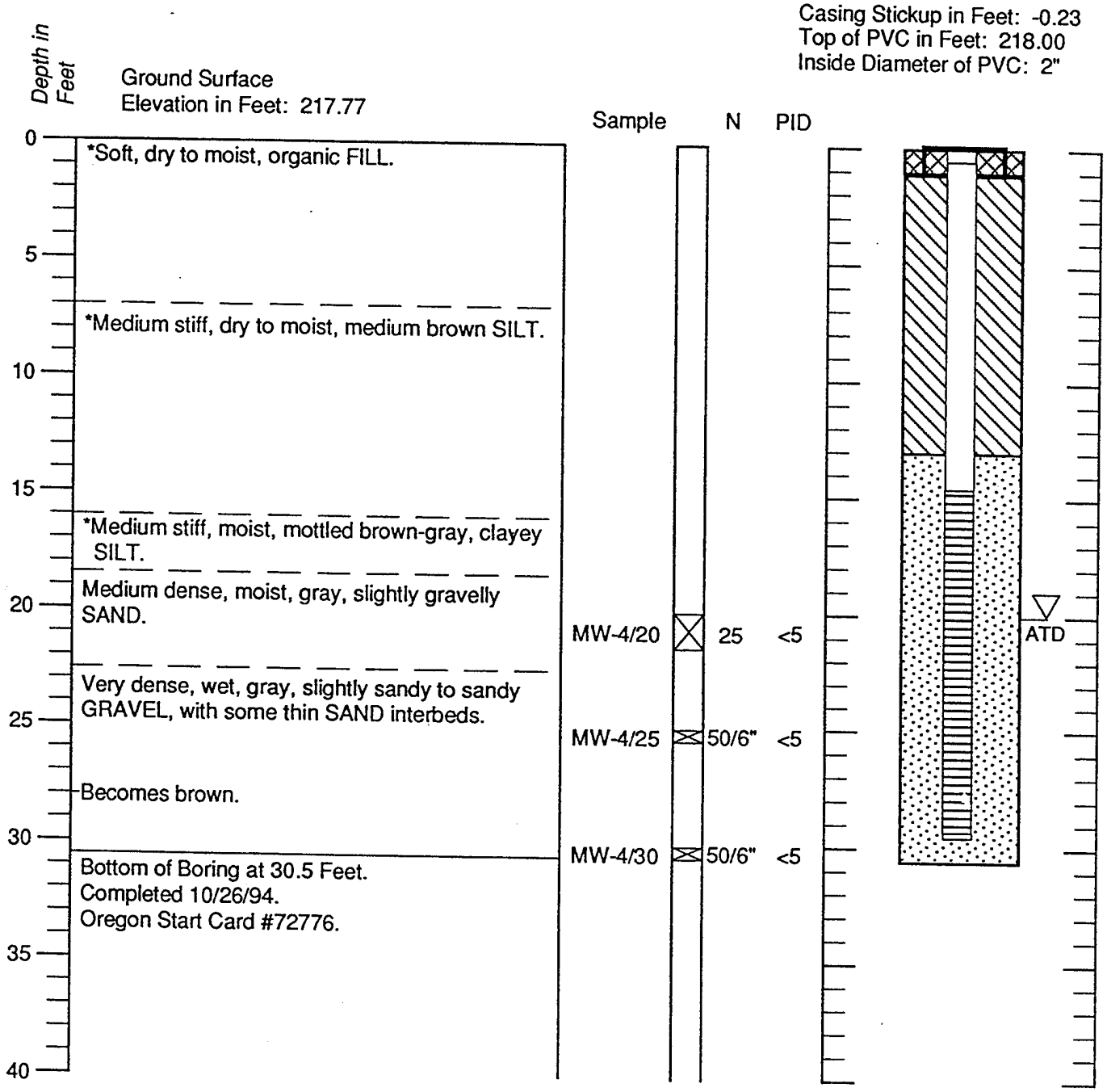
Boring Log and Construction Data For Monitoring Well MW-4

Boring Log and Construction Data for Monitoring Well MW-4

Geologic Log

Monitoring Well Design

Casing Stickup in Feet: -0.23
Top of PVC in Feet: 218.00
Inside Diameter of PVC: 2"



1. Refer to Figure A-1 for explanation of descriptions and symbols.
2. Soil descriptions and stratum lines are interpretive and actual changes may be gradual.
3. *Overdrilled previously existing well MW-4. Descriptions from 0 to 18.5 feet based on log for previous well by others.
4. Groundwater level, if indicated, is at time of drilling (ATD) or for date specified. Level may vary with time.
5. Elevations are relative to Oreon State Highway Department Benchmark B-192 (elevation = 224.557 feet msl).

HARTCROWSER
J-5334-05 12/94
Figure A-3

Appendix II

Chronological Record of Tests Performed at the Chevron Site

Chronological Record of Tests Performed at the Chevron Site

Test	Well	Date	Injection Solution Makeup*
1	MW-2	6/20/95	Oxygen Sparged
2	MW-2	6/23/95	Oxygen Sparged
3	MW-2	6/28/95	Oxygen Sparged
4	MW-2	6/30/95	Oxygen Sparged
5	MW-8	7/11/95	Oxygen Sparged
6	MW-8	7/14/95	Oxygen Sparged
7	MW-4	7/18/95	Oxygen Sparged
8	MW-4	7/20/95	Oxygen Sparged
9	MW-2	7/24/95	Oxygen Sparged
10	MW-2	7/28/95	Oxygen Sparged
11	MW-4	8/2/95	Nitrate/Nitrogen Sparged
12	MW-2	8/4/95	Nitrate/Nitrogen Sparged
13	MW-4	8/7/95	Nitrate/Nitrogen Sparged
14	MW-11	8/9/95	Hydrogen Peroxide
15	MW-4	8/15/95	Sulfate/Hydrogen Sparged
16	MW-2	8/17/95	Nitrite/Sulfate/Hydrogen Sparged
17	MW-2	8/18/95	Nitrate/Nitrogen Sparged
18	MW-4	8/22/95	Nitrite/Nitrogen Sparged
19	MW-4	8/24/95	Iron(III)-EDTA/Nitrogen Sparged
20	MW-4	9/6/95	Hydrogen Sparged
21	MW-2	9/7/95	Test aborted prior to injection
22	MW-4	9/13/95	Nitrate/Nitrogen Sparged

* A bromide tracer was used in all tests.

Appendix III

Field Notes and Calculations for Nitrate Injection Tests

Field Test #11
Well MW-4
02 August 1995

Initial Groundwater Information

Component	Concentration	
	mV	*mg/l*
Bromide	161.6	1.12
Nitrate-N	N/A	0
DO	N/A	0.01

GW Temperature 22 °C

Injection Phase

Solution Type	Volume	Bromide			Nitrate-N		Temp	Injection Rate	
		Conc.		Mass	Conc.	Mass	°C	Time	Flow Rate
	Liters	*mV*	*mg/l*	*mg*	*mg/l*	*mg*		*min*	*L/min*
NO_3/Bromide	105	56	90.99	9553.74	4.5	472.50	18	72.0	1.46
Clean Water	35	195	0.28	9.79	0	0.00	18	22.6	1.55
Total	140			9563.53		472.50			

Mass Balance

Solution Component	Mass		Percent
	Injected	Recovered	Recovered
	mg	*mg*	
Bromide	9563.53	8562.02	89.53%
Nitrate-N	472.50	147.75	31.27%

Mass Utilization Rate

Centroid of Mass	92.39	minutes
NO_3-N Utilization Rate	0.012	mg/l-min

Bromide Standard Curve

Standard Concentration		Conductance
mg/l	LOG(PPM)	mV
5	0.70	125.9
10	1.00	108.2
20	1.30	92.7
40	1.60	76.8
60	1.78	66.1
80	1.90	58.8
100	2.00	53.2
120	2.08	49.4

Regression Output:

Constant		164.39
Std Err of Y Est		0.6252
R Squared		0.9996
No. of Observations		8
Degrees of Freedom		6
X Coefficient(s)	-55.33	
Std Err of Coef.	0.47	

Field Test #11
Well MW-4
02 August 1995

Time	Volume			Bromide				Nitrate-N		
	Recorded	Corrected	Extr./Inj.	Conduct.	Conc.	Mass	C/Co	Conc.	Mass	C/Co
minutes	*liters*	*liters*		*mV*	*mg/l*	*mg*		*mg/l*	*mg*	
6.73	10.00	2.50	0.02	97.60	16.11		0.18	0.60		0.13
10.08	15.00	7.50	0.05	87.02	25.02	102.83	0.28		8.00	
13.42	20.00	12.50	0.09	76.80	38.29	158.27	0.42	1.00		0.22
16.92	25.00	17.50	0.13	72.30	46.17	211.14	0.51		12.50	
20.17	30.00	22.50	0.16	69.30	52.31	246.21	0.57	1.50		0.33
23.75	35.00	27.50	0.20	67.70	55.91	270.56	0.61		17.50	
28.67	40.00	32.50	0.23	66.80	58.05	284.90	0.64	2.00		0.44
31.67	45.00	37.50	0.27	68.60	53.86	279.76	0.59		17.50	
34.42	50.00	42.50	0.30	68.70	53.63	268.73	0.59	1.50		0.33
37.83	55.00	47.50	0.34	70.80	49.15	256.95	0.54		11.50	
40.00	60.00	52.50	0.38	71.30	48.13	243.20	0.53	0.80		0.18
43.75	65.00	57.50	0.41	72.90	45.03	232.92	0.49		9.00	
46.00	70.00	62.50	0.45	73.80	43.38	221.03	0.48	1.00		0.22
49.00	75.00	67.50	0.48	75.00	41.26	211.60	0.45		7.00	
51.67	80.00	72.50	0.52	76.40	38.93	200.48	0.43	0.40		0.09
54.75	85.00	77.50	0.55	78.00	36.42	188.37	0.40		6.00	
57.75	90.00	82.50	0.59	79.10	34.79	178.03	0.38	0.80		0.18
61.67	95.00	87.50	0.63	81.10	32.01	167.01	0.35		8.00	
64.17	100.00	92.50	0.66	81.90	30.96	157.44	0.34	0.80		0.18
67.17	105.00	97.50	0.70	83.10	29.46	151.05	0.32		6.00	
70.17	110.00	102.50	0.73	84.40	27.90	143.40	0.31	0.40		0.09
72.92	115.00	107.50	0.77	85.20	26.99	137.24	0.30		5.00	
75.67	120.00	112.50	0.80	86.10	26.00	132.47	0.29	0.60		0.13
78.25	125.00	117.50	0.84	86.80	25.25	128.13	0.28		4.50	
81.33	130.00	122.50	0.88	87.50	24.53	124.45	0.27	0.30		0.07
84.08	135.00	127.50	0.91	88.30	23.72	120.63	0.26		2.50	
87.17	140.00	132.50	0.95	89.50	22.57	115.73	0.25	0.20		0.04
90.17	145.00	137.50	0.98	90.20	21.92	111.22	0.24		2.50	

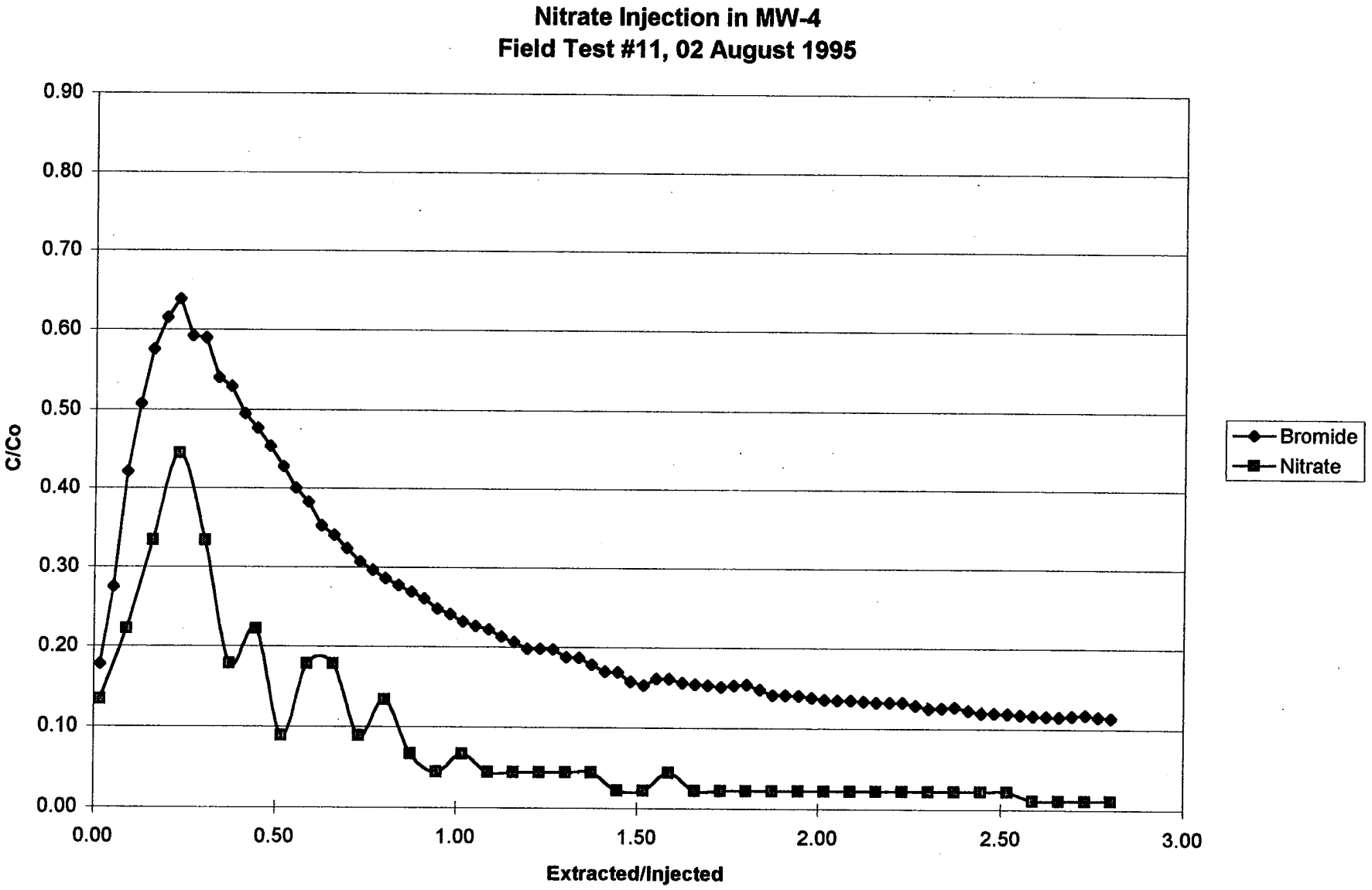
Field Test #11
Well MW-4
02 August 1995

Time	Volume			Bromide				Nitrate-N		
	Recorded	Corrected	Extr./Inj.	Conduct.	Conc.	Mass	C/Co	Conc.	Mass	C/Co
minutes	*liters*	*liters*		*mV*	*mg/l*	*mg*		*mg/l*	*mg*	
93.17	150.00	142.50	1.02	91.10	21.11	107.59	0.23	0.30		0.07
96.00	155.00	147.50	1.05	91.70	20.59	104.27	0.23		2.50	
98.92	160.00	152.50	1.09	92.20	20.17	101.91	0.22	0.20		0.04
101.50	165.00	157.50	1.13	93.20	19.35	98.79	0.21		2.00	
104.83	170.00	162.50	1.16	94.00	18.71	95.15	0.21	0.20		0.04
108.83	175.00	167.50	1.20	95.00	17.95	91.66	0.20		2.00	
111.83	180.00	172.50	1.23	95.00	17.95	89.76	0.20	0.20		0.04
115.33	185.00	177.50	1.27	95.10	17.88	89.57	0.20		2.00	
117.83	190.00	182.50	1.30	96.30	17.01	87.21	0.19	0.20		0.04
120.75	195.00	187.50	1.34	96.40	16.94	84.85	0.19		2.00	
123.92	200.00	192.50	1.38	97.50	16.18	82.78	0.18	0.20		0.04
129.67	205.00	197.50	1.41	98.70	15.39	78.92	0.17		1.50	
131.75	210.00	202.50	1.45	98.80	15.33	76.79	0.17	0.10		0.02
134.50	215.00	207.50	1.48	100.60	14.22	73.86	0.16		1.00	
138.00	220.00	212.50	1.52	101.20	13.87	70.22	0.15	0.10		0.02
141.00	225.00	217.50	1.55	100.00	14.58	71.12	0.16		1.50	
143.50	230.00	222.50	1.59	100.00	14.58	72.89	0.16	0.20		0.04
146.29	235.00	227.50	1.63	100.70	14.16	71.85	0.16		1.50	
149.08	240.00	232.50	1.66	101.00	13.98	70.36	0.15	0.10		0.02
151.92	245.00	237.50	1.70	101.25	13.84	69.56	0.15		1.00	
154.75	250.00	242.50	1.73	101.50	13.70	68.84	0.15	0.10		0.02
158.13	255.00	247.50	1.77	101.25	13.84	68.84	0.15		1.00	
161.50	260.00	252.50	1.80	101.00	13.98	69.56	0.15	0.10		0.02
164.58	265.00	257.50	1.84	102.00	13.41	68.50	0.15		1.00	
167.65	270.00	262.50	1.88	103.10	12.81	65.57	0.14	0.10		0.02
170.78	275.00	267.50	1.91	103.20	12.76	63.94	0.14		1.00	
173.92	280.00	272.50	1.95	103.30	12.71	63.67	0.14	0.10		0.02
176.96	285.00	277.50	1.98	103.70	12.50	63.01	0.14		1.00	
180.00	290.00	282.50	2.02	104.10	12.29	61.97	0.14	0.10		0.02

Field Test #11
Well MW-4
02 August 1995

Time	Volume			Bromide				Nitrate-N		
	Recorded	Corrected	Extr./Inj.	Conduct.	Conc.	Mass	C/Co	Conc.	Mass	C/Co
minutes	*liters*	*liters*		*mV*	*mg/l*	*mg*		*mg/l*	*mg*	
183.25	295.00	287.50	2.05	104.20	12.24	61.33	0.13		1.00	
186.50	300.00	292.50	2.09	104.20	12.24	61.20	0.13	0.10		0.02
189.50	305.00	297.50	2.13	104.50	12.09	60.82	0.13		1.00	
192.50	310.00	302.50	2.16	104.70	11.99	60.19	0.13	0.10		0.02
195.42	315.00	307.50	2.20	104.70	11.99	59.94	0.13		1.00	
198.33	320.00	312.50	2.23	104.70	11.99	59.94	0.13	0.10		0.02
201.42	325.00	317.50	2.27	105.30	11.69	59.20	0.13		1.00	
204.50	330.00	322.50	2.30	106.10	11.31	57.51	0.12	0.10		0.02
207.75	335.00	327.50	2.34	105.90	11.40	56.79	0.13		1.00	
211.00	340.00	332.50	2.38	105.70	11.50	57.26	0.13	0.10		0.02
214.17	345.00	337.50	2.41	106.50	11.12	56.56	0.12		1.00	
217.33	350.00	342.50	2.45	107.10	10.85	54.93	0.12	0.10		0.02
220.54	355.00	347.50	2.48	107.20	10.80	54.13	0.12		1.00	
223.75	360.00	352.50	2.52	107.30	10.76	53.91	0.12	0.10		0.02
227.38	365.00	357.50	2.55	107.50	10.67	53.57	0.12		0.75	
231.00	370.00	362.50	2.59	107.80	10.54	53.02	0.12	0.05		0.01
233.54	375.00	367.50	2.63	107.90	10.49	52.58	0.12		0.50	
236.08	380.00	372.50	2.66	108.10	10.41	52.25	0.11	0.05		0.01
239.21	385.00	377.50	2.70	107.80	10.54	52.36	0.12		0.50	
242.33	390.00	382.50	2.73	107.50	10.67	53.02	0.12	0.05		0.01
245.17	395.00	387.50	2.77	108.00	10.45	52.80	0.11		0.50	
248.00	400.00	392.50	2.80	108.30	10.32	51.93	0.11	0.05		0.01

Total Recovered Bromide = 8562.02 mg
Total Recovered Nitrate-N = 147.75 mg
Extraction Flow Rate = 1.61 L/min


Nitrate Injection in MW-4
Field Test #11, 02 August 1995
C/Co
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00
0.50
1.00
1.50
2.00
2.50
3.00
Extracted/Injected
Bromide
Nitrate

Field Test #12
Well MW-2
04 August 1995

Initial Groundwater Information

Component	Concentration	
	mV	*mg/l*
Bromide	159.8	1.76
Nitrate-N	N/A	0.1
DO	N/A	0.4

GW Temperature 20 °C

Injection Phase

Solution Type	Volume	Bromide			Nitrate-N		Temp	Injection Rate	
		Conc.		Mass	Conc.	Mass	°C	Time	Flow Rate
	Liters	*mV*	*mg/l*	*mg*	*mg/l*	*mg*		*min*	*L/min*
NO_3/Bromide	58	55.8	102.62	5951.79	5	290.00	19	39.0	1.49
Clean Water	30	201	0.35	10.54	0	0.00	19	33.8	0.89
Total	88			5962.33		290.00			

Mass Balance

Solution Component	Mass		Percent Recovered
	Injected *mg*	Recovered *mg*	
Bromide	5962.33	5418.07	90.87%
Nitrate-N	290.00	212.75	73.36%

Mass Utilization Rate

Centroid of Mass	44.63 minutes
NO_3-N Utilization Rate	0.0075 mg/l-min

Bromide Standard Curve

Standard Concentration mg/l	LOG(PPM)	Conductance mV
5	0.70	132.4
10	1.00	116.8
20	1.30	96.6
40	1.60	79.8
60	1.78	70.3
80	1.90	62
100	2.00	56.6
120	2.08	51.4

Regression Output:

Constant		174.24
Std Err of Y Est		0.8585
R Squared		0.9993
No. of Observations		8
Degrees of Freedom		6
X Coefficient(s)	-58.89	
Std Err of Coef.	0.65	

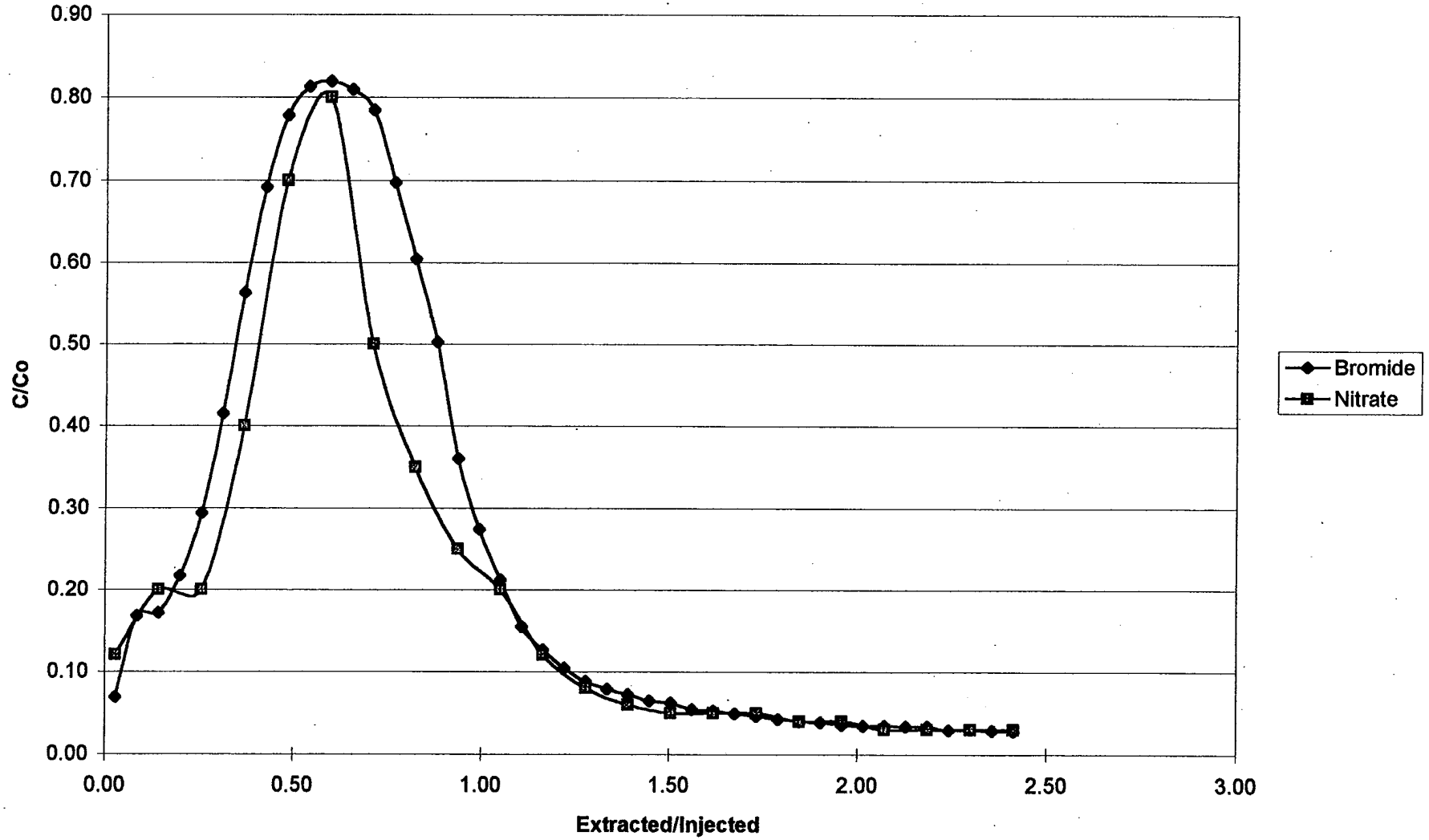
Field Test #12
Well MW-2
04 August 1995

Time	Volume			Bromide				Nitrate-N		
	Recorded	Corrected	Extr./Inj.	Conduct.	Conc.	Mass	C/Co	Conc.	Mass	C/Co
minutes	*liters*	*liters*		*mV*	*mg/l*	*mg*		*mg/l*	*mg*	
2.00	10.00	2.50	0.03	124.1	7.10		0.07	0.60		0.12
5.00	15.00	7.50	0.09	101.6	17.12	60.56	0.17		8.00	
8.00	20.00	12.50	0.14	101	17.53	86.62	0.17	1.00		0.20
11.33	25.00	17.50	0.20	94.9	22.25	99.43	0.22		10.00	
14.50	30.00	22.50	0.26	87.1	30.18	131.07	0.29	1.00		0.20
18.50	35.00	27.50	0.31	78.3	42.57	181.89	0.41		15.00	
21.67	40.00	32.50	0.37	70.5	57.76	250.83	0.56	2.00		0.40
25.33	45.00	37.50	0.43	65.2	71.06	322.03	0.69		27.50	
29.00	50.00	42.50	0.48	62.2	79.90	377.39	0.78	3.50		0.70
32.50	55.00	47.50	0.54	61.1	83.41	408.28	0.81		37.50	
36.25	60.00	52.50	0.60	60.9	84.07	418.69	0.82	4.00		0.80
40.17	65.00	57.50	0.65	61.2	83.09	417.88	0.81		32.50	
43.67	70.00	62.50	0.71	62	80.53	409.03	0.78	2.50		0.50
47.50	75.00	67.50	0.77	65	71.61	380.35	0.70		21.25	
51.25	80.00	72.50	0.82	68.7	61.97	333.95	0.60	1.75		0.35
54.67	85.00	77.50	0.88	73.4	51.57	283.83	0.50		15.00	
58.67	90.00	82.50	0.94	81.9	36.98	221.38	0.36	1.25		0.25
62.50	95.00	87.50	0.99	88.9	28.13	162.78	0.27		11.25	
66.00	100.00	92.50	1.05	95.5	21.73	124.65	0.21	1.00		0.20
70.00	105.00	97.50	1.11	103.6	15.83	93.91	0.15		8.00	
73.75	110.00	102.50	1.16	108.7	12.97	72.01	0.13	0.60		0.12
77.67	115.00	107.50	1.22	113.7	10.67	59.09	0.10		5.00	
81.50	120.00	112.50	1.28	117.9	9.05	49.30	0.09	0.40		0.08
85.17	125.00	117.50	1.34	120.8	8.08	42.83	0.08		3.50	
88.50	130.00	122.50	1.39	123	7.42	38.74	0.07	0.30		0.06
92.50	135.00	127.50	1.45	125.7	6.67	35.22	0.07		2.75	

Field Test #12
Well MW-2
04 August 1995

Time	Volume			Bromide				Nitrate-N		
	Recorded	Corrected	Extr./Inj.	Conduct.	Conc.	Mass	C/Co	Conc.	Mass	C/Co
minutes	*liters*	*liters*		*mV*	*mg/l*	*mg*		*mg/l*	*mg*	
96.00	140.00	132.50	1.51	126.8	6.39	32.66	0.06	0.25		0.05
99.75	145.00	137.50	1.56	130.2	5.60	29.97	0.05		2.50	
103.50	150.00	142.50	1.62	131.3	5.36	27.39	0.05	0.25		0.05
107.33	155.00	147.50	1.68	132.8	5.05	26.04	0.05		2.50	
110.17	160.00	152.50	1.73	134.4	4.75	24.51	0.05	0.25		0.05
114.33	165.00	157.50	1.79	136.4	4.39	22.85	0.04		2.25	
118.67	170.00	162.50	1.85	138	4.12	21.29	0.04	0.20		0.04
122.67	175.00	167.50	1.90	139	3.97	20.23	0.04		2.00	
126.00	180.00	172.50	1.96	140.9	3.68	19.12	0.04	0.20		0.04
130.25	185.00	177.50	2.02	141.7	3.57	18.13	0.03		1.75	
133.33	190.00	182.50	2.07	141.7	3.57	17.85	0.03	0.15		0.03
137.50	195.00	187.50	2.13	142.5	3.46	17.57	0.03		1.50	
150.33	200.00	192.50	2.19	142.5	3.46	17.30	0.03	0.15		0.03
154.00	205.00	197.50	2.24	145.8	3.04	16.25	0.03		1.50	
159.00	210.00	202.50	2.30	145.4	3.09	15.32	0.03	0.15		0.03
152.17	215.00	207.50	2.36	146.2	2.99	15.20	0.03		1.50	
156.08	220.00	212.50	2.41	147.2	2.88	14.68	0.03	0.15		0.03

Total Recovered Bromide = 5418.07 mg
Total Recovered Nitrate-N = 212.75 mg
Extraction Flow Rate = 1.41 L/min


Nitrate Injection in MW-2
Field Test #12, 04 August 1995
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
C/Co
0.00
0.50
1.00
1.50
2.00
2.50
3.00
Extracted/Injected
Bromide
Nitrate

Field Test #13
Well MW-4
07 August 1995

Initial Groundwater Information

Component	Concentration	
	mV	*mg/l*
Bromide	157	1.51
NO_3-N	N/A	0
NO_2-N	N/A	0
DO	N/A	0.01

GW Temperature 22 °C

Injection Phase

Solution Type	Volume	Bromide			Nitrate-N		Temp	Injection Rate	
		Conc.		Mass	Conc.	Mass	°C	Time	Flow Rate
	Liters	*mV*	*mg/l*	*mg*	*mg/l*	*mg*		*min*	*L/min*
NO_3/Bromide	98	51.3	103.32	10125.69	5	490.00	19	86.1	1.14
Clean Water	35	200	0.27	9.51	0	0.00	19	24.3	1.44
Total	133			10135.20		490.00			

Mass Balance

Solution Component	Mass		Percent Recovered
	Injected *mg*	Recovered *mg*	
Bromide	10135.20	8426.76	83.14%
Nitrate-N	490.00	193.00	39.39%
Nitrite-N*	297.00	9.35	3.15%

* The NO_2 injected value is equal to the NO_3 utilized.

Mass Utilization Rate

Centroid of Mass	89.47	minutes
NO_3-N Utilization Rate	0.011	mg/l-min
NO_2-N Utilization Rate	0.011	mg/l-min

Bromide Standard Curve

Standard Concentration		Conductance
mg/l	LOG(PPM)	mV
5	0.70	126.9
10	1.00	109.8
20	1.30	92.8
40	1.60	75.5
60	1.78	64.2
80	1.90	57.2
100	2.00	52.3
120	2.08	47.9

Regression Output:

Constant		167.39
Std Err of Y Est		0.4659
R Squared		0.9998
No. of Observations		8
Degrees of Freedom		6
X Coefficient(s)	-57.64	
Std Err of Coef.	0.35	

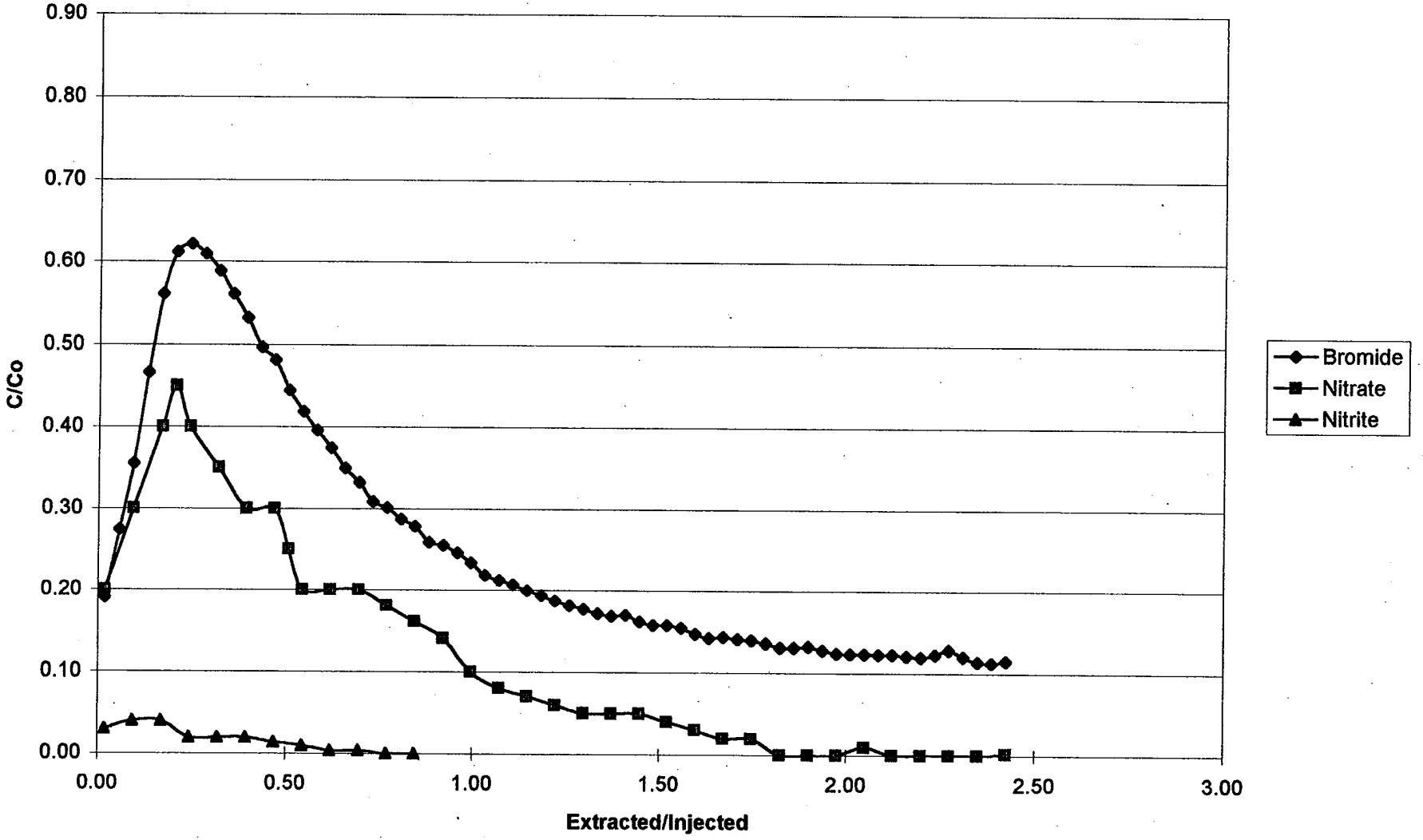
Field Test #13
Well MW-4
07 August 1995

Time	Volume			Bromide				Nitrate-N			Nitrite-N		
	Recorded	Corrected	Extr./Inj.	Conduct.	Conc.	Mass	C/Co	Conc.	Mass	C/Co	Conc.	Mass	C/Co
minutes	*liters*	*liters*		*mV*	*mg/l*	*mg*		*mg/l*	*mg*		*mg/l*	*mg*	
4.00	10.00	2.50	0.02	92.9	19.61		0.19	1.00		0.20	0.15		0.03
8.00	15.00	7.50	0.06	83.7	28.32	119.81	0.27		12.50			1.75	
12.00	20.00	12.50	0.09	77.2	36.71	162.58	0.36	1.50		0.30	0.20		0.04
15.25	25.00	17.50	0.13	70.4	48.17	212.22	0.47		17.50			2.00	
19.00	30.00	22.50	0.17	65.8	57.89	265.17	0.56	2.00	10.63	0.40	0.20		0.04
23.17	35.00	27.50	0.21	63.6	63.21	302.76	0.61	2.25	10.63	0.45		1.50	
26.25	40.00	32.50	0.24	63.2	64.23	318.60	0.62	2.00		0.40	0.10		0.02
30.00	45.00	37.50	0.28	63.7	62.96	317.97	0.61		18.75			1.00	
33.50	50.00	42.50	0.32	64.6	60.74	309.24	0.59	1.75		0.35	0.10		0.02
37.67	55.00	47.50	0.36	65.8	57.89	296.57	0.56		16.25			1.00	
41.67	60.00	52.50	0.39	67.1	54.96	282.14	0.53	1.50		0.30	0.10		0.02
45.75	65.00	57.50	0.43	68.8	51.35	265.79	0.50		15.00			0.85	
48.75	70.00	62.50	0.47	69.6	49.74	252.73	0.48	1.50	6.88	0.30	0.07		0.01
53.33	75.00	67.50	0.51	71.6	45.92	239.14	0.44	1.25	5.63	0.25		0.60	
57.25	80.00	72.50	0.55	73.1	43.25	222.92	0.42	1.00		0.20	0.05		0.01
60.75	85.00	77.50	0.58	74.5	40.90	210.36	0.40		10.00			0.35	
64.75	90.00	82.50	0.62	75.9	38.67	198.92	0.37	1.00		0.20	0.02		0.00
68.75	95.00	87.50	0.66	77.6	36.13	187.01	0.35		10.00			0.20	
72.00	100.00	92.50	0.70	78.9	34.30	176.09	0.33	1.00		0.20	0.02		0.00
76.00	105.00	97.50	0.73	80.7	31.92	165.57	0.31		9.50			0.10	
79.25	110.00	102.50	0.77	81.3	31.17	157.72	0.30	0.90		0.18	0.00		0.00
83.50	115.00	107.50	0.81	82.5	29.71	152.19	0.29		8.50			0.00	
86.50	120.00	112.50	0.85	83.3	28.77	146.20	0.28	0.80		0.16	0.00		0.00
90.67	125.00	117.50	0.88	85.1	26.78	138.88	0.26		7.50				
94.17	130.00	122.50	0.92	85.5	26.35	132.82	0.26	0.70		0.14			
98.25	135.00	127.50	0.96	86.4	25.42	129.44	0.25		6.00				
102.33	140.00	132.50	1.00	87.7	24.14	123.89	0.23	0.50		0.10			
107.33	145.00	137.50	1.03	89.4	22.55	116.71	0.22		4.50				
110.17	150.00	142.50	1.07	90.1	21.93	111.20	0.21	0.40		0.08			
113.75	155.00	147.50	1.11	90.8	21.32	108.13	0.21		3.75				
117.50	160.00	152.50	1.15	91.7	20.57	104.74	0.20	0.35		0.07			
121.17	165.00	157.50	1.18	92.5	19.92	101.24	0.19		3.25				
125.08	170.00	162.50	1.22	93.4	19.22	97.86	0.19	0.30		0.06			
129.33	175.00	167.50	1.26	94.1	18.69	94.78	0.18		2.75				
133.00	180.00	172.50	1.30	94.7	18.25	92.34	0.18	0.25		0.05			
137.00	185.00	177.50	1.33	95.5	17.67	89.80	0.17		2.50				

Field Test #13
Well MW-4
07 August 1995

Time	Volume			Bromide				Nitrate-N			Nitrite-N		
	Recorded	Corrected	Extr./Inj.	Conduct.	Conc.	Mass	C/Co	Conc.	Mass	C/Co	Conc.	Mass	C/Co
minutes	*liters*	*liters*		*mV*	*mg/l*	*mg*		*mg/l*	*mg*		*mg/l*	*mg*	
140.50	190.00	182.50	1.37	96	17.32	87.49	0.17	0.25		0.05			
144.33	195.00	187.50	1.41	95.8	17.46	86.97	0.17		2.50				
148.50	200.00	192.50	1.45	97	16.65	85.27	0.16	0.25		0.05			
152.17	205.00	197.50	1.48	97.7	16.19	82.08	0.16		2.25				
156.17	210.00	202.50	1.52	97.7	16.19	80.93	0.16	0.20		0.04			
160.50	215.00	207.50	1.56	98.2	15.87	80.13	0.15		1.75				
164.08	220.00	212.50	1.60	99.5	15.06	77.32	0.15	0.15		0.03			
168.67	225.00	217.50	1.64	100.3	14.59	74.13	0.14		1.25				
171.75	230.00	222.50	1.67	100.1	14.71	73.24	0.14	0.10		0.02			
175.50	235.00	227.50	1.71	100.5	14.47	72.95	0.14		1.00				
179.25	240.00	232.50	1.75	100.8	14.30	71.94	0.14	0.10		0.02			
183.00	245.00	237.50	1.79	101.4	13.96	70.66	0.14		0.50				
186.75	250.00	242.50	1.82	102.3	13.47	68.58	0.13	0.00		0.00			
190.50	255.00	247.50	1.86	102.3	13.47	67.35	0.13		0.00				
195.00	260.00	252.50	1.90	102.1	13.58	67.62	0.13	0.00		0.00			
199.00	265.00	257.50	1.94	102.9	13.15	66.82	0.13		0.00				
203.50	270.00	262.50	1.97	103.7	12.74	64.72	0.12	0.00		0.00			
207.67	275.00	267.50	2.01	103.8	12.69	63.56	0.12		0.25				
211.08	280.00	272.50	2.05	103.8	12.69	63.43	0.12	0.05		0.01			
214.50	285.00	277.50	2.09	104	12.58	63.18	0.12		1.50				
218.50	290.00	282.50	2.12	103.9	12.64	63.05	0.12			0.00			
222.50	295.00	287.50	2.16	104.3	12.43	62.67	0.12						
226.50	300.00	292.50	2.20	104.6	12.29	61.80	0.12			0.00			
231.93	305.00	297.50	2.24	104	12.58	62.18	0.12						
236.00	310.00	302.50	2.27	102.8	13.20	64.47	0.13			0.00			
239.00	315.00	307.50	2.31	104.5	12.34	63.85	0.12						
242.67	320.00	312.50	2.35	105.8	11.71	60.12	0.11			0.00			
247.83	325.00	317.50	2.39	106.1	11.57	58.21	0.11						
255.50	330.00	322.50	2.42	105.5	11.85	58.56	0.11	0.01		0.00			

Total Recovered Bromide =	8426.76	mg
Total Recovered Nitrate-N =	193.00	mg
Total Recovered Nitrite-N =	9.35	mg
Extraction Flow Rate =	1.29	L/min


Nitrate Injection in MW-4
Field Test #13, 07 August 1995
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
C/Co
0.00
0.50
1.00
1.50
2.00
2.50
3.00
Extracted/Injected
Bromide
Nitrate
Nitrite

Field Test #17
Well MW-2
18 August 1995

Initial Groundwater Information

Component	Concentration	
	mV	*mg/l*
Bromide	141.5	4.02
NO_3-N	N/A	0.1
NO_2-N	N/A	0
DO	N/A	0.8

GW Temperature 19 °C

Injection Phase

Solution Type	Volume	Bromide			Nitrate-N		Temp	Injection Rate	
		Conc.		Mass	Conc.	Mass	°C	TIme	Flow Rate
	Liters	*mV*	*mg/l*	*mg*	*mg/l*	*mg*		*min*	*L/min*
NO_3/Bromide	58	59.8	93.57	5427.15	4.75	275.50	19	86.1	0.67
Clean Water	30	191	0.60	17.91	0	0.00	19	24.3	1.23
Total	88			5445.06		275.50			

Mass Balance

Solution Component	Mass		Percent Recovered
	Injected *mg*	Recovered *mg*	
Bromide	5445.06	5114.06	93.92%
Nitrate-N	275.50	195.00	70.78%
Nitrite-N*	80.50	3.875	4.81%

* The NO_2 injected value is equal to the NO_3 utilized.

Mass Utilization Rate

Centroid of Mass	66.62	minutes
NO_3-N Utilization Rate	0.0052	mg/l-min
NO_2-N Utilization Rate	0.0049	mg/l-min

Bromide Standard Curve

Standard Concentration		Conductance
mg/l	LOG(PPM)	mV
5	0.70	136.2
10	1.00	117.1
20	1.30	100.5
40	1.60	80.7
60	1.78	72.6
80	1.90	64.1
100	2.00	57
120	2.08	53.8

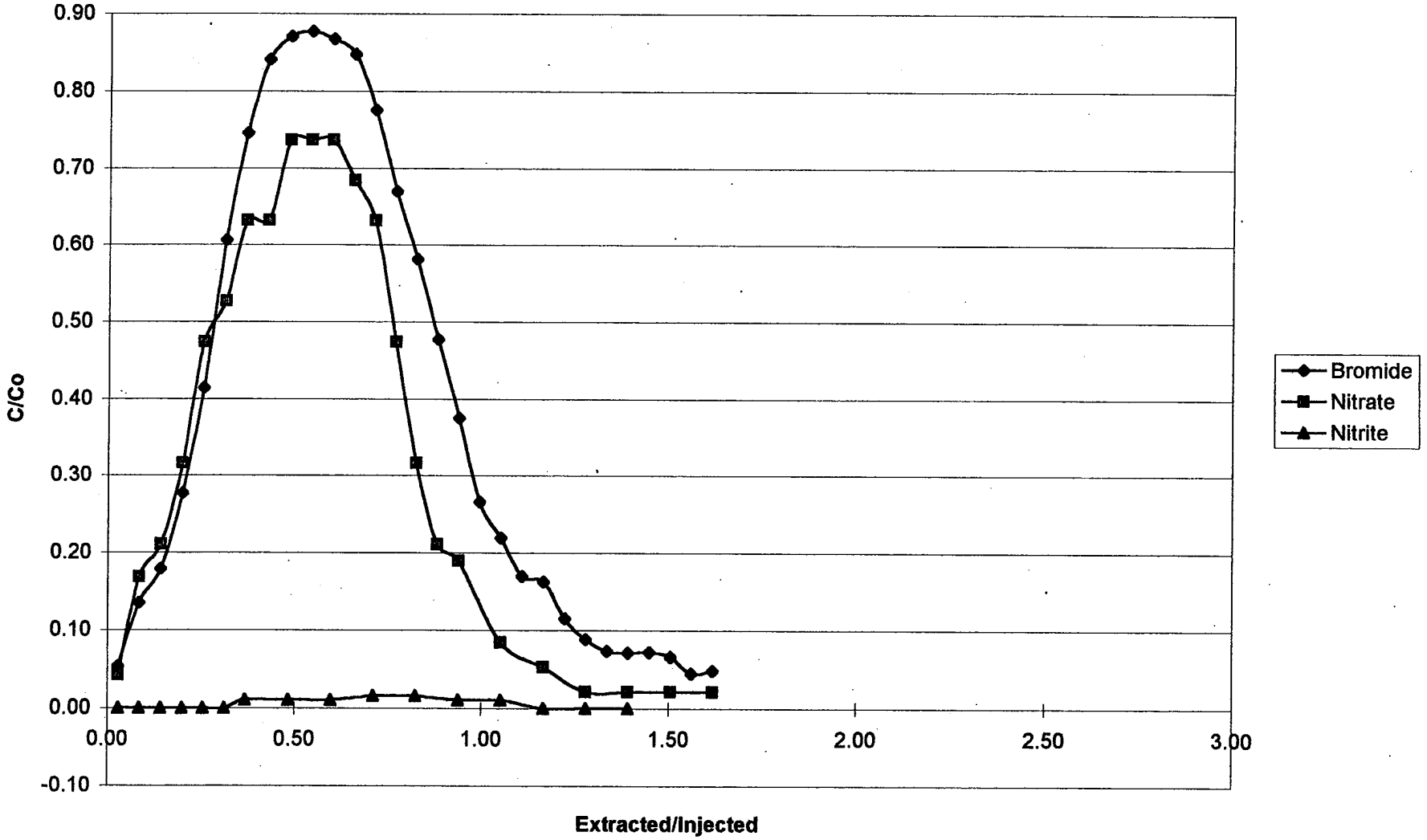
Regression Output:

Constant		177.6
Std Err of Y Est		0.955
R Squared		0.9991
No. of Observations		8
Degrees of Freedom		6
X Coefficient(s)	-59.76	
Std Err of Coef.	0.72	

Field Test #17
Well MW-2
18 August 1995

Time	Volume			Bromide				Nitrate-N			Nitrite		
	Recorded	Corrected	Extr./Inj.	Conduct.	Conc.	Mass	C/Co	Conc.	Mass	C/Co	Conc.	Mass	C/Co
minutes	*liters*	*liters*		*mV*	*mg/l*	*mg*		*mg/l*	*mg*		*mg/l*	*mg*	
4.50	10.00	2.50	0.03	136.100	4.95		0.05	0.200		0.04	0.000		0.00
10.50	15.00	7.50	0.09	111.800	12.62	43.92	0.13	0.800	2.50	0.17	0.000	0.00	0.00
15.00	20.00	12.50	0.14	104.500	16.72	73.35	0.18	1.000	4.50	0.21	0.000	0.00	0.00
20.50	25.00	17.50	0.20	93.200	25.84	106.40	0.28	1.500	6.25	0.32	0.000	0.00	0.00
26.17	30.00	22.50	0.26	82.700	38.72	161.41	0.41	2.250	9.38	0.47	0.000	0.00	0.00
31.50	35.00	27.50	0.31	72.800	56.71	238.57	0.61	2.500	11.88	0.53	0.000	0.00	0.00
37.50	40.00	32.50	0.37	67.400	69.82	316.31	0.75	3.000	13.75	0.63	0.050	0.13	0.01
42.83	45.00	37.50	0.43	64.300	78.68	371.24	0.84	3.000	15.00	0.63		0.50	
49.00	50.00	42.50	0.48	63.400	81.45	400.33	0.87	3.500	16.25	0.74	0.050		0.01
55.50	55.00	47.50	0.54	63.200	82.08	408.84	0.88	3.500	17.50	0.74		0.50	
60.75	60.00	52.50	0.60	63.500	81.14	408.06	0.87	3.500	17.50	0.74	0.050		0.01
67.75	65.00	57.50	0.65	64.100	79.29	401.06	0.85	3.250	16.88	0.68		0.63	
74.50	70.00	62.50	0.71	66.400	72.56	379.62	0.78	3.000	15.63	0.63	0.075		0.02
84.00	75.00	67.50	0.77	70.200	62.68	338.11	0.67	2.250	13.13	0.47		0.75	
88.83	80.00	72.50	0.82	73.900	54.35	292.58	0.58	1.500	9.38	0.32	0.075		0.02
96.50	85.00	77.50	0.88	79.000	44.66	247.52	0.48	1.000	6.25	0.21		0.63	
102.33	90.00	82.50	0.94	85.300	35.03	199.22	0.37	0.900	4.75	0.19	0.050		0.01
111.75	95.00	87.50	0.99	94.300	24.77	149.50	0.26		6.50			0.50	
114.17	100.00	92.50	1.05	99.200	20.51	113.19	0.22	0.400		0.08	0.050		0.01
118.00	105.00	97.50	1.11	105.900	15.84	90.87	0.17		3.25			0.25	
120.50	110.00	102.50	1.16	107.000	15.18	77.56	0.16	0.250		0.05	0.000		0.00
128.00	115.00	107.50	1.22	116.000	10.73	64.80	0.11		1.75			0.00	
138.33	120.00	112.50	1.28	122.900	8.23	47.41	0.09	0.100		0.02	0.000		0.00
139.33	125.00	117.50	1.34	127.700	6.84	37.67	0.07		1.00				
142.50	130.00	122.50	1.39	128.400	6.66	33.74	0.07	0.100		0.02	0.000		0.00
148.25	135.00	127.50	1.45	128.200	6.71	33.42	0.07		1.00				
151.83	140.00	132.50	1.51	130.600	6.12	32.06	0.07	0.100		0.02			
157.17	145.00	137.50	1.56	140.600	4.16	25.69	0.04		1.00				
161.00	150.00	142.50	1.62	138.700	4.48	21.59	0.05	0.100		0.02			

Total Recovered Bromide = 5114.06 mg
Total Recovered Nitrate-N = 195.00 mg
Total Recovered Nitrite-N = 3.875 mg
Extraction Flow Rate = 0.93 L/min


Nitrate Injection in MW-2
Field Test #17, 18 August 1995
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
C/Co
0.00
0.50
1.00
1.50
2.00
2.50
3.00
Extracted/Injected
Bromide
Nitrate
Nitrite

Field Test #22
Well MW-4
13 September 1995

Initial Groundwater Information

Component	Concentration	
	mV	*mg/l*
Bromide	138.8	5.61
NO_3-N	N/A	0
NO_2-N	N/A	0
DO	N/A	0.01

GW Temperature 21 °C

Injection Phase

Solution Type	Volume	Bromide			Nitrate-N		Temp	Injection Rate	
		Conc.		Mass	Conc.	Mass	°C	Time	Flow Rate
	Liters	*mV*	*mg/l*	*mg*	*mg/l*	*mg*		*min*	*L/min*
NO_3/Bromide	90	59.1	107.65	9688.84	4.5	405.00	19	99.7	0.90
Clean Water	35	200	0.58	20.28	0	0.00	19	29.8	1.18
Total	125			9709.13		405.00			

Mass Balance

Solution Component	Mass		Percent Recovered
	Injected	Recovered	
	mg	*mg*	
Bromide	9709.13	9671.80	99.62%
Nitrate-N	405.00	84.00	20.74%
Nitrite-N*	321.00	1.00	0.31%

* The NO_2 injected value is equal to the NO_3 utilized.

Mass Utilization Rate

Centroid of Mass	75.89	minutes
NO_3-N Utilization Rate	0.013	mg/l-min
NO_2-N Utilization Rate	0.012	mg/l-min

Bromide Standard Curve

Standard Concentration		Conductance
mg/l	LOG(PPM)	mV
5	0.70	142.6
10	1.00	122.8
20	1.30	104
40	1.60	85.4
60	1.78	75
80	1.90	66.9
100	2.00	61.1
120	2.08	56.8

Regression Output:

Constant		185.29
Std Err of Y Est		0.5045
R Squared		0.9998
No. of Observations		8
Degrees of Freedom		6
X Coefficient(s)	-62.10	
Std Err of Coef.	0.38	

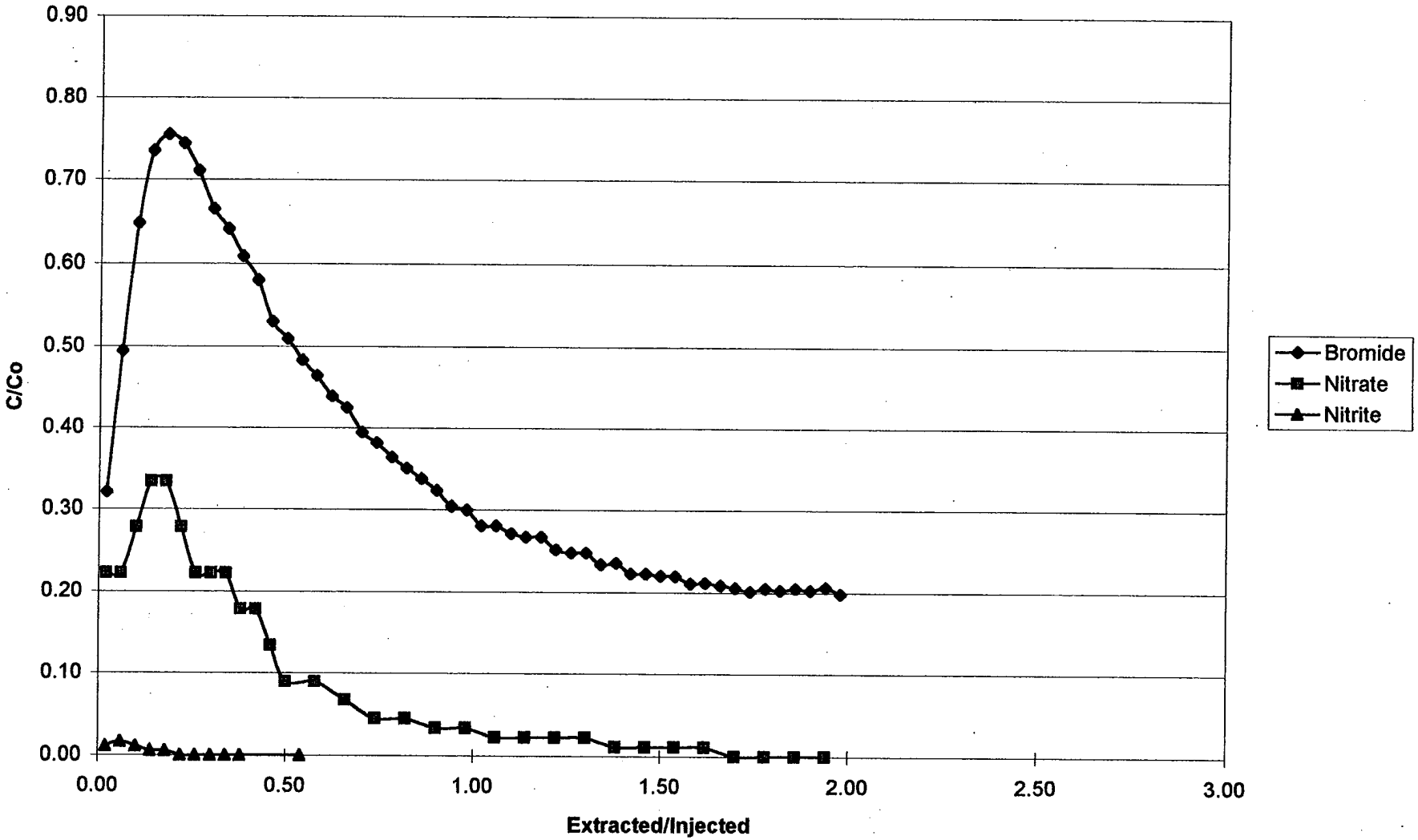
Field Test #22
Well MW-4
13 September 1995

Time	Volume			Bromide				Nitrate-N			Nitrite-N		
	Recorded	Corrected	Extr./Inj.	Conduct.	Conc.	Mass	C/Co	Conc.	Mass	C/Co	Conc.	Mass	C/Co
minutes	*liters*	*liters*		*mV*	*mg/l*	*mg*		*mg/l*	*mg*		*mg/l*	*mg*	
5.50	10.00	2.50	0.02	89.8	34.49		0.32	1.00		0.22	0.05		0.01
8.50	15.00	7.50	0.06	78.1	53.22	219.27	0.49	1.00	5.00	0.22	0.08	0.31	0.02
11.67	20.00	12.50	0.10	70.8	69.76	307.45	0.65	1.25	5.63	0.28	0.05	0.31	0.01
15.17	25.00	17.50	0.14	67.4	79.14	372.25	0.74	1.50	6.88	0.33	0.03	0.19	0.01
19.00	30.00	22.50	0.18	66.7	81.22	400.88	0.75	1.50	7.50	0.33	0.03	0.13	0.01
23.00	35.00	27.50	0.22	67.1	80.02	403.09	0.74	1.25	6.88	0.28	0.00	0.06	0.00
26.17	40.00	32.50	0.26	68.3	76.54	391.40	0.71	1.00	5.63	0.22	0.00	0.00	0.00
29.17	45.00	37.50	0.30	70.1	71.60	370.34	0.67	1.00	5.00	0.22	0.00	0.00	0.00
33.00	50.00	42.50	0.34	71.1	68.99	351.47	0.64	1.00	5.00	0.22	0.00	0.00	0.00
37.75	55.00	47.50	0.38	72.5	65.50	336.23	0.61	0.80	4.50	0.18	0.00	0.00	0.00
41.17	60.00	52.50	0.42	73.8	62.42	319.80	0.58	0.80	4.00	0.18			
45.25	65.00	57.50	0.46	76.2	57.10	298.81	0.53	0.60	3.50	0.13			
49.25	70.00	62.50	0.50	77.3	54.82	279.81	0.51	0.40	2.50	0.09			
53.75	75.00	67.50	0.54	78.7	52.05	267.17	0.48		4.00			0.00	0.00
57.00	80.00	72.50	0.58	79.8	49.97	255.04	0.46	0.40		0.09			
66.25	85.00	77.50	0.62	81.3	47.26	243.08	0.44		3.50				
65.50	90.00	82.50	0.66	82.2	45.71	232.45	0.42	0.30		0.07			
69.75	95.00	87.50	0.70	84.2	42.45	220.40	0.39		2.50		0.00		
73.00	100.00	92.50	0.74	85.1	41.05	208.75	0.38	0.20		0.04			
77.50	105.00	97.50	0.78	86.4	39.12	200.44	0.36		2.00				
81.17	110.00	102.50	0.82	87.4	37.70	192.05	0.35	0.20		0.04			
85.33	115.00	107.50	0.86	88.4	36.33	185.06	0.34		1.75				
89.67	120.00	112.50	0.90	89.6	34.74	177.67	0.32	0.15		0.03			
93.83	125.00	117.50	0.94	91.2	32.74	168.72	0.30		1.50				
97.67	130.00	122.50	0.98	91.6	32.26	162.51	0.30	0.15		0.03			
101.75	135.00	127.50	1.02	93.4	30.18	156.10	0.28		1.25				
104.75	140.00	132.50	1.06	93.4	30.18	150.89	0.28	0.10		0.02			
109.17	145.00	137.50	1.10	94.3	29.19	148.41	0.27		1.00				
113.25	150.00	142.50	1.14	94.7	28.76	144.86	0.27	0.10		0.02			
117.00	155.00	147.50	1.18	94.7	28.76	143.79	0.27		1.00				
120.75	160.00	152.50	1.22	96.3	27.10	139.65	0.25	0.10		0.02			
125.17	165.00	157.50	1.26	96.7	26.70	134.51	0.25		1.00				
129.50	170.00	162.50	1.30	96.7	26.70	133.51	0.25	0.10		0.02			

Field Test #22
Well MW-4
13 September 1995

Time	Volume			Bromide				Nitrate-N			Nitrite-N		
	Recorded	Corrected	Extr./Inj.	Conduct.	Conc.	Mass	C/Co	Conc.	Mass	C/Co	Conc.	Mass	C/Co
minutes	*liters*	*liters*		*mV*	*mg/l*	*mg*		*mg/l*	*mg*		*mg/l*	*mg*	
132.75	175.00	167.50	1.34	98.3	25.16	129.67	0.23		0.75				
136.25	180.00	172.50	1.38	98.1	25.35	126.29	0.24	0.05		0.01			
141.33	185.00	177.50	1.42	99.6	23.98	123.33	0.22		0.50				
145.50	190.00	182.50	1.46	99.6	23.98	119.90	0.22	0.05		0.01			
149.83	195.00	187.50	1.50	99.9	23.71	119.24	0.22		0.50				
153.25	200.00	192.50	1.54	100	23.63	118.35	0.22	0.05		0.01			
157.33	205.00	197.50	1.58	101.1	22.68	115.77	0.21		0.50				
162.08	210.00	202.50	1.62	101	22.77	113.62	0.21	0.05		0.01			
165.75	215.00	207.50	1.66	101.4	22.43	113.00	0.21		0.25				
170.00	220.00	212.50	1.70	101.8	22.10	111.33	0.21	0.00		0.00			
174.17	225.00	217.50	1.74	102.4	21.62	109.29	0.20		0.00				
177.25	230.00	222.50	1.78	101.9	22.02	109.09	0.20	0.00		0.00			
181.67	235.00	227.50	1.82	102.2	21.78	109.49	0.20		0.00				
184.50	240.00	232.50	1.86	101.9	22.02	109.49	0.20	0.00		0.00			
189.17	245.00	237.50	1.90	102.2	21.78	109.49	0.20		0.00				
193.25	250.00	242.50	1.94	101.7	22.18	109.90	0.21	0.00		0.00			
197.17	255.00	247.50	1.98	102.8	21.30	108.70	0.20						

Total Recovered Bromide = 9671.80 mg
Total Recovered Nitrate-N = 84.00 mg
Total Recovered Nitrite-N = 1.00 mg
Extraction Flow Rate = 1.29 L/min


Nitrate Injection in MW-4
Field Test #22, 13 September 1995
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
C/Co
0.00
0.50
1.00
1.50
2.00
2.50
3.00
Extracted/Injected
Bromide
Nitrate
Nitrite

Appendix IV

Field Notes and Calculations for Nitrite Injection Tests

Field Test #16
Well MW-2
17 August 1995

Initial Groundwater Information

Component	Concentration	
	mV	*mg/l*
Bromide	162.5	1.28
NO_2-N	N/A	0.02
DO	N/A	0.8

GW Temperature 19.5 °C

Injection Phase

Solution Type	Volume	Bromide			Nitrite-N		Temp	Injection Rate	
		Conc.		Mass	Conc.	Mass	°C	TIme	Flow Rate
	Liters	*mV*	*mg/l*	*mg*	*mg/l*	*mg*		*min*	*L/min*
NO_2/Bromide	55	53.7	115.90	6374.37	0.5	27.50	19	39.0	1.41
Clean Water	30	191	0.39	11.78	0	0.00	19	33.8	0.89
Total	85			6386.15		27.50			

Mass Balance

Solution Component	Mass		Percent
	Injected	Recovered	Recovered
	mg	*mg*	
Bromide	6386.15	5614.10	87.91%
Nitrite-N	27.50	19.80	72.00%

Mass Utilization Rate

Centroid of Mass	57.90	minutes
NO_2-N Utilization Rate	0.00069	mg/l-min

Bromide Standard Curve

Standard Concentration		Conductance
mg/l	LOG(PPM)	mV
5	0.70	128
10	1.00	113.7
20	1.30	97.1
40	1.60	79.9
60	1.78	70.7
80	1.90	62.3
100	2.00	57.1
120	2.08	51.5

Regression Output:

Constant		168.44
Std Err of Y Est		1.13193
R Squared		0.9996
No. of Observations		8
Degrees of Freedom		6
X Coefficient(s)	-55.59	
Std Err of Coef.	0.86	

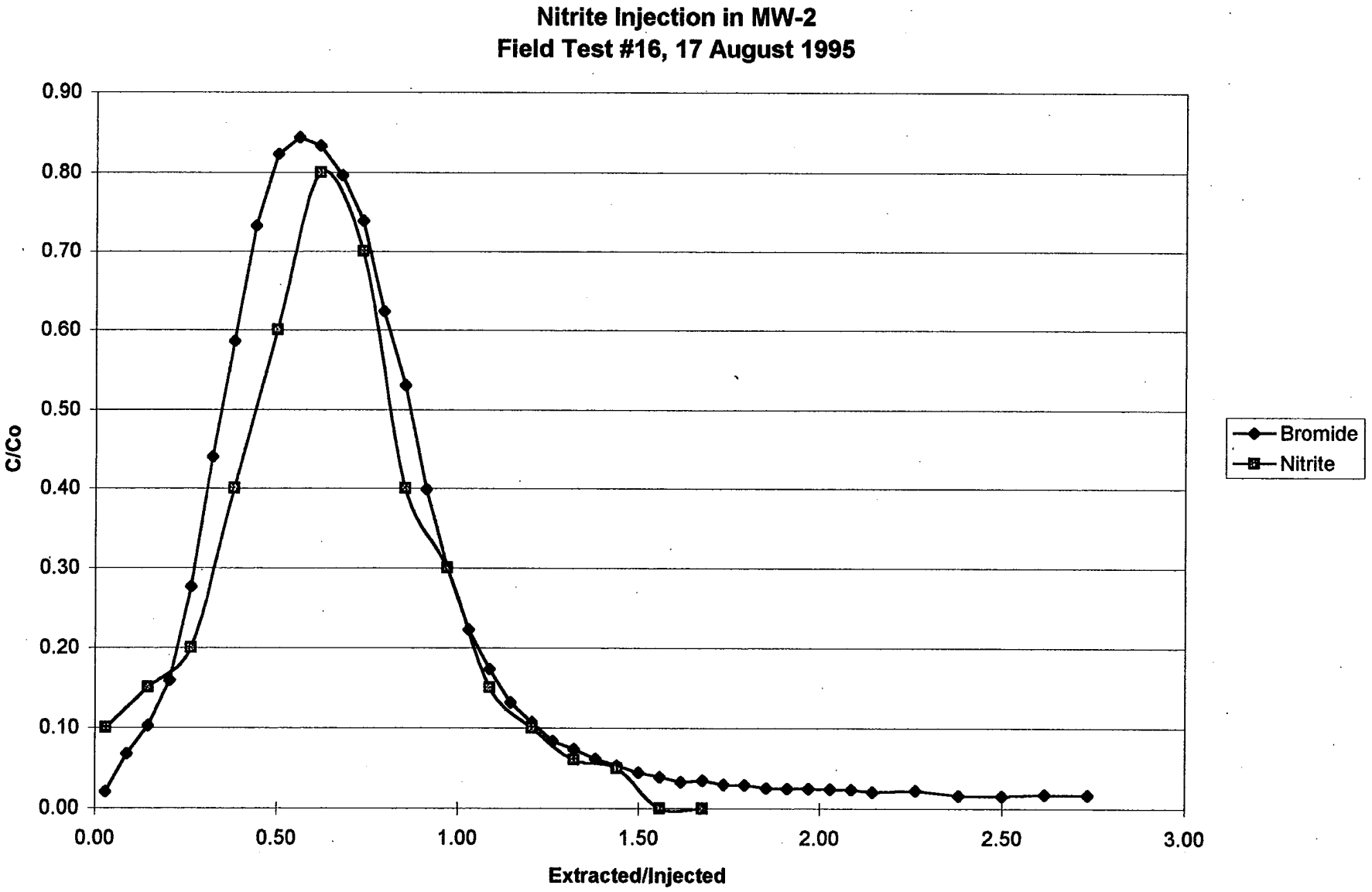
Field Test #16
Well MW-2
17 August 1995

Time	Volume			Bromide				Nitrite-N		
	Recorded	Corrected	Extr./Inj.	Conduct.	Conc.	Mass	C/Co	Conc.	Mass	C/Co
minutes	*liters*	*liters*		*mV*	*mg/l*	*mg*		*mg/l*	*mg*	
9.25	10.00	2.50	0.03	147.90	2.34		0.02	0.05		0.10
15.33	15.00	7.50	0.09	118.70	7.85	25.47	0.07		0.63	
19.50	20.00	12.50	0.15	108.70	11.88	49.31	0.10	0.08		0.15
23.33	25.00	17.50	0.21	98.20	18.35	75.56	0.16		0.88	
27.17	30.00	22.50	0.26	84.70	32.09	126.10	0.28	0.10		0.20
30.50	35.00	27.50	0.32	73.50	51.04	207.83	0.44		1.50	
34.00	40.00	32.50	0.38	66.60	67.92	297.40	0.59	0.20		0.40
38.00	45.00	37.50	0.44	61.20	84.95	382.18	0.73		2.50	
42.08	50.00	42.50	0.50	58.40	95.39	450.86	0.82	0.30		0.60
46.33	55.00	47.50	0.56	57.80	97.80	482.98	0.84		3.50	
50.00	60.00	52.50	0.62	58.10	96.59	485.96	0.83	0.40		0.80
54.50	65.00	57.50	0.68	59.20	92.29	472.18	0.80		3.75	
58.00	70.00	62.50	0.74	61.00	85.66	444.85	0.74	0.35		0.70
63.00	75.00	67.50	0.79	65.10	72.28	394.83	0.62		2.75	
66.67	80.00	72.50	0.85	69.00	61.49	334.43	0.53	0.20		0.40
71.25	85.00	77.50	0.91	75.90	46.21	269.26	0.40		1.75	
75.33	90.00	82.50	0.97	82.70	34.86	202.68	0.30	0.15		0.30
79.67	95.00	87.50	1.03	90.00	25.77	151.58	0.22		1.13	
83.17	100.00	92.50	1.09	96.10	20.01	114.45	0.17	0.08		0.15
87.50	105.00	97.50	1.15	102.70	15.23	88.10	0.13		0.63	
91.50	110.00	102.50	1.21	107.60	12.43	69.14	0.11	0.05		0.10
96.00	115.00	107.50	1.26	113.70	9.65	55.21	0.08		0.40	
100.00	120.00	112.50	1.32	116.60	8.56	45.54	0.07	0.03		0.06
104.00	125.00	117.50	1.38	121.10	7.11	39.17	0.06		0.28	
107.83	130.00	122.50	1.44	124.80	6.10	33.00	0.05	0.03		0.05
112.00	135.00	127.50	1.50	129.10	5.10	27.99	0.04		0.13	

Field Test #16
Well MW-2
17 August 1995

Time	Volume			Bromide				Nitrite-N		
	Recorded	Corrected	Extr./Inj.	Conduct.	Conc.	Mass	C/Co	Conc.	Mass	C/Co
minutes	*liters*	*liters*		*mV*	*mg/l*	*mg*		*mg/l*	*mg*	
116.00	140.00	132.50	1.56	132.10	4.51	24.02	0.04	0.00		0.00
121.00	145.00	137.50	1.62	136.30	3.79	20.73	0.03		0.00	
125.00	150.00	142.50	1.68	135.10	3.98	19.41	0.03	0.00		0.00
129.33	155.00	147.50	1.74	138.90	3.40	18.45	0.03			
133.00	160.00	152.50	1.79	139.20	3.36	16.89	0.03			
138.25	165.00	157.50	1.85	142.30	2.95	15.78	0.03			
142.50	170.00	162.50	1.91	143.20	2.84	14.49	0.02			
147.00	175.00	167.50	1.97	142.90	2.88	14.31	0.02			
150.67	180.00	172.50	2.03	143.50	2.81	14.22	0.02			
155.50	185.00	177.50	2.09	144.30	2.72	13.82	0.02			
160.00	190.00	182.50	2.15	148.10	2.32	12.60	0.02			
168.50	200.00	192.50	2.26	145.60	2.58	24.49	0.02			
175.00	210.00	202.50	2.38	153.30	1.87	22.24	0.02			
187.33	220.00	212.50	2.50	154.40	1.79	18.30	0.02			
196.17	230.00	222.50	2.62	152.00	1.98	18.82	0.02			
202.83	240.00	232.50	2.74	152.70	1.92	19.48	0.02			

Total Recovered Bromide = 5614.10 mg
Total Recovered Nitrite-N = 19.80 mg
Extraction Flow Rate = 1.18 L/min


Nitrite Injection in MW-2
Field Test #16, 17 August 1995
C/Co
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00
0.50
1.00
1.50
2.00
2.50
3.00
Extracted/Injected
Bromide
Nitrite

Field Test #18
Well MW-4
22 August 1995

Initial Groundwater Information

Component	Concentration	
	mV	*mg/l*
Bromide	170.9	1.32
NO_2-N	N/A	0
DO	N/A	0.01

GW Temperature 21 °C

Injection Phase

Solution Type	Volume	Bromide			Nitrite-N		Temp	Injection Rate	
		Conc.		Mass	Conc.	Mass	°C	Time	Flow Rate
	Liters	*mV*	*mg/l*	*mg*	*mg/l*	*mg*		*min*	*L/min*
NO_2/Bromide	84	60.1	93.74	7874.56	0.5	42.00	18	86.5	0.97
Clean Water	30	191	0.61	18.20	0	0.00	18	27.5	1.09
Total	114			7892.76		42.00			

Mass Balance

Solution Component	Mass		Percent Recovered
	Injected	Recovered	
	mg	*mg*	
Bromide	7892.76	7898.06	100.07%
Nitrite-N	42.00	3.30	7.86%

Mass Utilization Rate

Centroid of Mass	72.57	minutes
NO_2-N Utilization Rate	0.0018	mg/l-min

Bromide Standard Curve

Standard Concentration		Conductance
mg/l	LOG(PPM)	mV
5	0.70	137
10	1.00	117.9
20	1.30	98.1
40	1.60	83.5
60	1.78	72.4
80	1.90	64.7
100	2.00	58.6
120	2.08	52.7

Regression Output:

Constant		178.02
Std Err of Y Est		1.1965
R Squared		0.9996
No. of Observations		8
Degrees of Freedom		6
X Coefficient(s)	-59.80	
Std Err of Coef.	0.90	

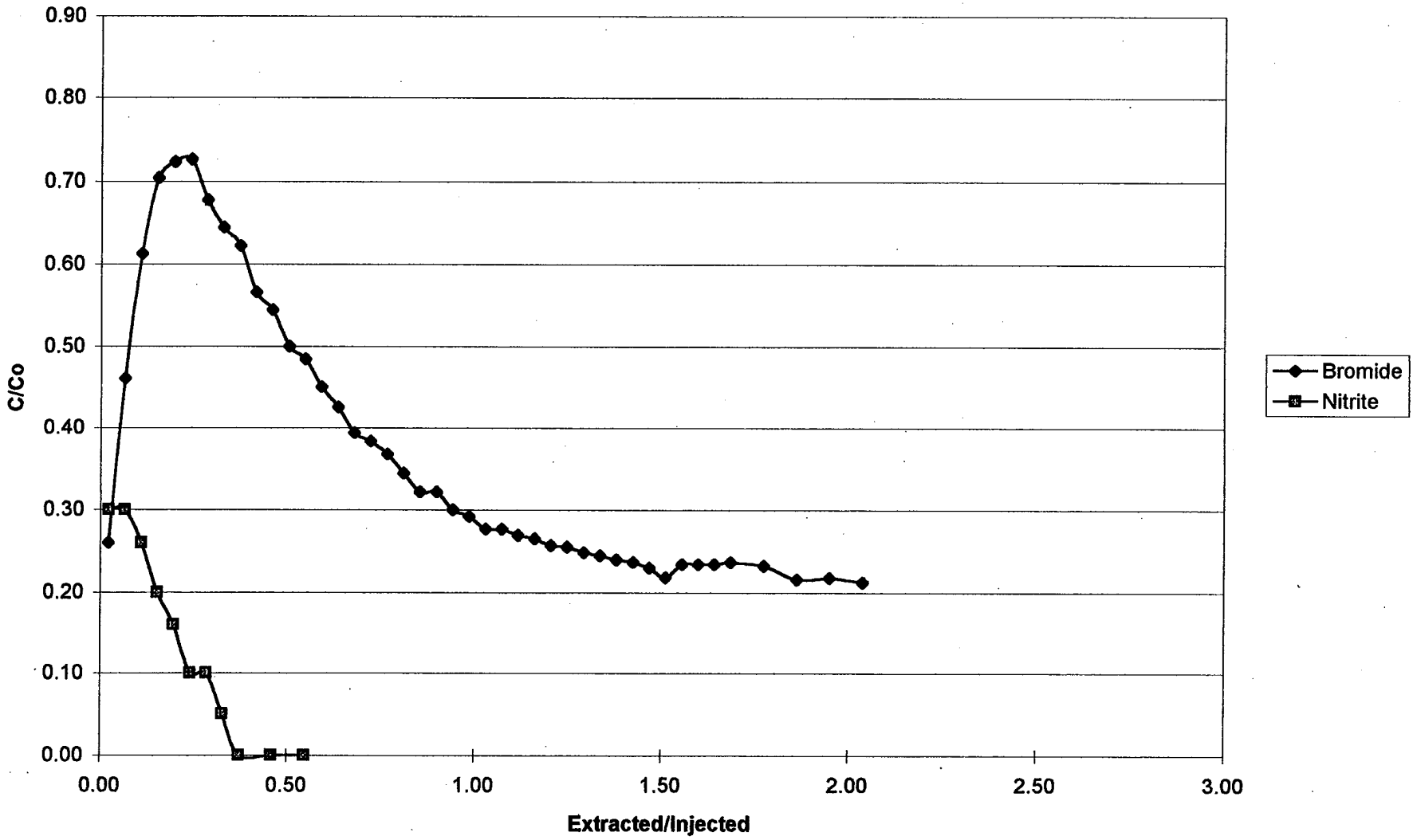
Field Test #18
Well MW-4
22 August 1995

Time	Volume			Bromide				Nitrite-N		
	Recorded	Corrected	Extr./Inj.	Conduct.	Conc.	Mass	C/Co	Conc.	Mass	C/Co
minutes	*liters*	*liters*		*mV*	*mg/l*	*mg*		*mg/l*	*mg*	
4.83	10.00	2.50	0.02	95.100	24.36		0.26	0.150		0.30
8.17	15.00	7.50	0.07	80.200	43.23	168.98	0.46	0.150	0.75	0.30
12.17	20.00	12.50	0.11	72.800	57.49	251.80	0.61	0.130	0.70	0.26
15.67	25.00	17.50	0.15	69.200	66.03	308.80	0.70	0.100	0.58	0.20
19.50	30.00	22.50	0.20	68.500	67.84	334.68	0.72	0.080	0.45	0.16
25.50	35.00	27.50	0.24	68.400	68.10	339.85	0.73	0.050	0.33	0.10
28.67	40.00	32.50	0.29	70.200	63.54	329.10	0.68	0.050	0.25	0.10
32.50	45.00	37.50	0.33	71.500	60.44	309.94	0.64	0.025	0.19	0.05
35.50	50.00	42.50	0.37	72.400	58.38	297.04	0.62	0.000	0.06	0.00
39.50	55.00	47.50	0.42	74.900	53.02	278.50	0.57		0.00	
42.50	60.00	52.50	0.46	75.900	51.02	260.10	0.54	0.000		0.00
46.33	65.00	57.50	0.50	78.100	46.87	244.73	0.50		0.00	
49.33	70.00	62.50	0.55	78.900	45.45	230.82	0.48	0.000		0.00
52.00	75.00	67.50	0.59	80.800	42.25	219.25	0.45			
56.67	80.00	72.50	0.64	82.300	39.88	205.30	0.43			
61.00	85.00	77.50	0.68	84.300	36.92	191.99	0.39			
63.83	90.00	82.50	0.72	85.000	35.94	182.14	0.38			
67.33	95.00	87.50	0.77	86.100	34.45	175.96	0.37			
71.00	100.00	92.50	0.81	87.800	32.26	166.78	0.34			
75.50	105.00	97.50	0.86	89.600	30.10	155.92	0.32			
78.00	110.00	102.50	0.90	89.600	30.10	150.52	0.32			
81.67	115.00	107.50	0.94	91.400	28.09	145.48	0.30			
84.50	120.00	112.50	0.99	92.100	27.34	138.57	0.29			
89.00	125.00	117.50	1.03	93.500	25.91	133.12	0.28			
91.50	130.00	122.50	1.07	93.500	25.91	129.53	0.28			
95.00	135.00	127.50	1.12	94.200	25.22	127.81	0.27			

Field Test #18
Well MW-4
22 August 1995

Time	Volume			Bromide				Nitrite-N		
	Recorded	Corrected	Extr./Inj.	Conduct.	Conc.	Mass	C/Co	Conc.	Mass	C/Co
minutes	*liters*	*liters*		*mV*	*mg/l*	*mg*		*mg/l*	*mg*	
98.83	140.00	132.50	1.16	94.600	24.83	125.12	0.26			
103.50	145.00	137.50	1.21	95.400	24.08	122.28	0.26			
106.50	150.00	142.50	1.25	95.600	23.89	119.93	0.25			
110.17	155.00	147.50	1.29	96.300	23.26	117.88	0.25			
115.17	160.00	152.50	1.34	96.700	22.90	115.41	0.24			
120.00	165.00	157.50	1.38	97.200	22.47	113.42	0.24			
125.17	170.00	162.50	1.43	97.500	22.21	111.69	0.24			
129.50	175.00	167.50	1.47	98.300	21.53	109.36	0.23			
133.50	180.00	172.50	1.51	99.600	20.48	105.05	0.22			
137.67	185.00	177.50	1.56	97.800	21.95	106.09	0.23			
140.75	190.00	182.50	1.60	97.800	21.95	109.77	0.23			
145.00	195.00	187.50	1.64	97.500	21.95	109.77	0.23			
148.17	200.00	192.50	1.69	98.000	22.21	220.81	0.24			
155.83	210.00	202.50	1.78	99.900	21.79	219.97	0.23			
163.00	220.00	212.50	1.86	99.700	20.25	210.17	0.22			
170.25	230.00	222.50	1.95	100.400	20.40	203.26	0.22			
179.75	240.00	232.50	2.04	98.900	19.86	201.33	0.21			
193.00	250.00	242.50	2.13	96.800	21.04	204.53	0.22			

Total Recovered Bromide = 7898.06 mg
Total Recovered Nitrite-N = 3.30 mg
Extraction Flow Rate = 1.34 L/min


Nitrite Injection in MW-4
Field Test #18, 22 August 1995
C/Co
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00
0.50
1.00
1.50
2.00
2.50
3.00
Extracted/Injected
Bromide
Nitrite

Appendix V

Field Notes and Calculations for Hydrogen Injection Test

Field Test #20
Well MW-4
06 September 1995

Initial Groundwater Information

Component	Concentration		
	Reading	*units*	*mg/l*
Bromide	170.2	mV	1.61
H_2	2.1	%	0.03
CH_4	2815	GC Area	6.68E-2
DO	N/A	N/A	0.01

GW Temperature 18 °C

Injection Phase

Solution Type	Volume	Bromide			Hydrogen		Temp	Injection Rate	
		Conc.		Mass	Conc.	Mass	°C	Time	Flow Rate
	Liters	*mV*	*mg/l*	*mg*	*mg/l*	*mg*		*min*	*L/min*
H_2/Bromide	115	61.9	88.42	10167.95	1.63	187.44	20	110.0	1.05
Clean Water	30	198.2	0.57	17.14	0	0.00	20	31.3	0.96
Total	145			10185.08		187.44			

Mass Balance

Solution Component	Mass		Percent Recovered
	Injected *mg*	Recovered *mg*	
Bromide	10185.08	9238.47	90.71%
Hydrogen	187.44	75.80	40.44%
Methane*	446.59	6.15	1.38%

* The CH_4 value is equal to the H_2 utilized on a 1:4 molar basis

Mass Utilization Rate

Centroid of Mass	72.80	minutes
H_2 Utilization Rate	0.0036	mg/L-min

Bromide Standard Curve

Standard Concentration		Conductance
mg/l	*Log(ppm)*	*mV*
5	0.70	139.6
10	1.00	120.1
20	1.30	102.3
40	1.60	84.2
60	1.78	72.5
80	1.90	65.3
100	2.00	58.3
120	2.08	52.7

Regression Output:

Constant		183.07
Std Err of Y Est		0.6787
R Squared		0.9996
No. of Observations		8
Degrees of Freedom		6
X Coefficient(s)	-62.25	
Std Err of Coef.	0.51	

Field Test #20
Well MW-4
06 September 1995

Gas Solubility in Water

	Concentration *mg/l*	Meter Reading
H_2 Saturated	1.63	100.00
CH_4 Saturated	25.01	
Temperature	20 Celcius	

Methane Standard Curve

Total Methane volume *microL*	Total Methane mass *mg*	Concentration Headspace *mg/l*	Concentration Water *mg/l*	Concentration GW *mg/l*	GC Area
1	6.66E-04	2.43E-02	9.14E-04	6.66E-02	2906
2.5	1.77E-03	6.03E-02	1.45E-02	1.77E-01	6713
5	3.54E-03	1.21E-01	2.89E-02	3.54E-01	13373
7.5	5.32E-03	1.81E-01	4.34E-02	5.32E-01	20961
10	7.09E-03	2.41E-01	5.79E-02	7.09E-01	28507

Regression Output:

Constant		0
Std Err of Y Est		430.019
R Squared		0.9983
No. of Observations		5
Degrees of Freedom		4
X Coefficient(s)	42149.20	
Std Err of Coef.	470.56	

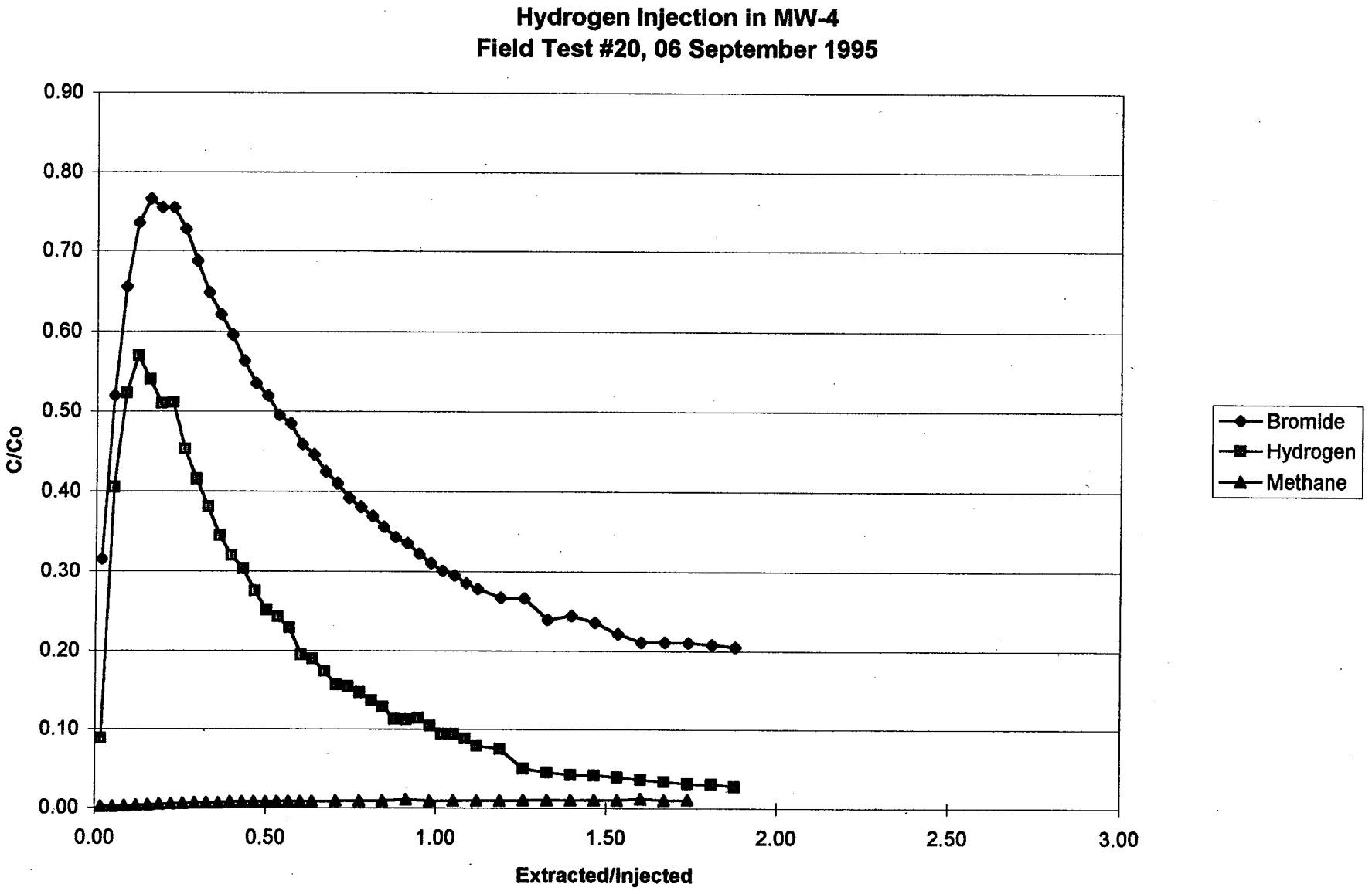
Field Test #20
Well MW-4
06 September 1995

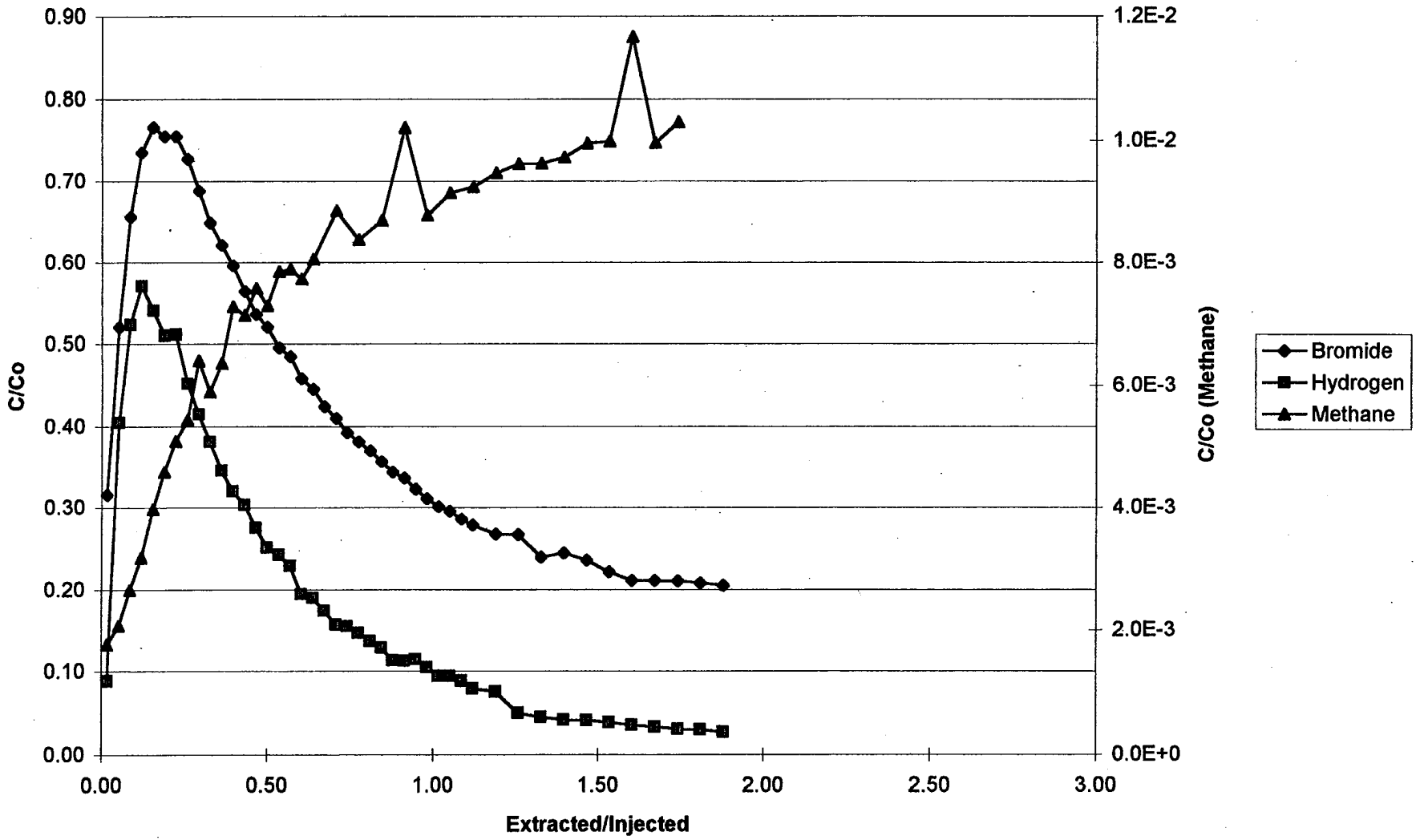
Time	Volume			Bromide				Hydrogen				Methane			
	Recorded	Corrected	Extr./Inj.	Conduct.	Conc.	Mass	C/Co	Meter	Conc.	Mass	C/Co	GC Area	Conc.	Mass	C/Co
minutes	*liters*	*liters*		*mV*	*mg/l*	*mg*		*%*	*mg/l*	*mg*			*mg/l*	*mg*	
7.67	10.00	2.50	0.02	93.10	27.88		0.32	8.80	0.14		0.09	483.00	1.15E-2		1.76E-3
11.00	15.00	7.50	0.05	79.60	45.94	184.55	0.52	40.50	0.66	2.01	0.41	568.00	1.35E-2	6.23E-2	2.07E-3
14.00	20.00	12.50	0.09	73.30	58.00	259.84	0.66	52.30	0.85	3.78	0.52	729.00	1.73E-2	7.69E-2	2.65E-3
17.33	25.00	17.50	0.12	70.20	65.04	307.59	0.74	57.00	0.93	4.45	0.57	875.00	2.08E-2	9.51E-2	3.18E-3
20.25	30.00	22.50	0.16	69.10	67.74	331.96	0.77	54.00	0.88	4.52	0.54	1092.00	2.59E-2	1.17E-1	3.97E-3
23.33	35.00	27.50	0.19	69.50	66.75	336.23	0.75	51.00	0.83	4.28	0.51	1257.00	2.98E-2	1.39E-1	4.57E-3
26.50	40.00	32.50	0.22	69.50	66.75	333.74	0.75	51.1	0.83	4.16	0.51	1398.00	3.32E-2	1.57E-1	5.09E-3
29.33	45.00	37.50	0.26	70.50	64.32	327.68	0.73	45.20	0.74	3.92	0.45	1495.00	3.55E-2	1.72E-1	5.44E-3
32.50	50.00	42.50	0.29	72.00	60.85	312.94	0.69	41.50	0.68	3.53	0.42	1758.00	4.17E-2	1.93E-1	6.40E-3
36.00	55.00	47.50	0.33	73.60	57.36	295.52	0.65	38.10	0.62	3.24	0.38	1619.00	3.84E-2	2.00E-1	5.89E-3
39.00	60.00	52.50	0.36	74.80	54.87	280.55	0.62	34.50	0.56	2.96	0.35	1747.00	4.14E-2	2.00E-1	6.36E-3
41.83	65.00	57.50	0.40	75.90	52.68	268.86	0.60	32.00	0.52	2.71	0.32	1995.00	4.73E-2	2.22E-1	7.26E-3
44.33	70.00	62.50	0.43	77.40	49.83	256.28	0.56	30.30	0.49	2.54	0.30	1957.00	4.64E-2	2.34E-1	7.12E-3
48.25	75.00	67.50	0.47	78.80	47.32	242.88	0.54	27.50	0.45	2.36	0.28	2079.00	4.93E-2	2.39E-1	7.57E-3
50.50	80.00	72.50	0.50	79.60	45.94	233.15	0.52	25.10	0.41	2.14	0.25	1998.00	4.74E-2	2.42E-1	7.27E-3
53.83	85.00	77.50	0.53	80.90	43.78	224.30	0.50	24.20	0.39	2.01	0.24	2155.00	5.11E-2	2.46E-1	7.84E-3
57.08	90.00	82.50	0.57	81.50	42.82	216.51	0.48	22.90	0.37	1.92	0.23	2166.00	5.14E-2	2.56E-1	7.88E-3
61.50	95.00	87.50	0.60	83.00	40.51	208.33	0.46	19.40	0.32	1.72	0.19	2120.00	5.03E-2	2.54E-1	7.71E-3
64.00	100.00	92.50	0.64	83.80	39.33	199.60	0.44	18.90	0.31	1.56	0.19	2212.00	5.25E-2	2.57E-1	8.05E-3
67.00	105.00	97.50	0.67	85.10	37.48	192.03	0.42	17.30	0.28	1.48	0.17			5.51E-1	
69.75	110.00	102.50	0.71	86.00	36.25	184.34	0.41	15.60	0.25	1.34	0.16	2430.00	5.77E-2		8.84E-3
73.00	115.00	107.50	0.74	87.20	34.68	177.34	0.39	15.40	0.25	1.26	0.15			5.61E-1	
75.83	120.00	112.50	0.78	88.00	33.67	170.88	0.38	14.60	0.24	1.22	0.15	2299.00	5.45E-2		8.37E-3
78.83	125.00	117.50	0.81	88.80	32.69	165.89	0.37	13.60	0.22	1.15	0.14			5.56E-1	
82.33	130.00	122.50	0.84	89.80	31.50	160.47	0.36	12.80	0.21	1.08	0.13	2388.00	5.67E-2		8.69E-3
86.00	135.00	127.50	0.88	90.80	30.36	154.64	0.34	11.30	0.18	0.98	0.11			6.16E-1	
88.50	140.00	132.50	0.91	91.40	29.69	150.12	0.34	11.20	0.18	0.92	0.11	2806.00	6.66E-2		1.02E-2
91.50	145.00	137.50	0.95	92.50	28.51	145.49	0.32	11.40	0.19	0.92	0.11			6.19E-1	
94.83	150.00	142.50	0.98	93.50	27.47	139.94	0.31	10.40	0.17	0.89	0.10	2411.00	5.72E-2		8.77E-3
98.17	155.00	147.50	1.02	94.40	26.57	135.11	0.30	9.40	0.15	0.81	0.09			5.84E-1	
101.50	160.00	152.50	1.05	94.90	26.08	131.64	0.30	9.40	0.15	0.77	0.09	2512.00	5.96E-2		9.14E-3
105.17	165.00	157.50	1.09	95.80	25.23	128.29	0.29	8.80	0.14	0.74	0.09			5.99E-1	
108.83	170.00	162.50	1.12	96.50	24.59	124.54	0.28	7.90	0.13	0.68	0.08	2538.00	6.02E-2		9.24E-3
114.83	180.00	172.50	1.19	97.60	23.61	240.96	0.27	7.50	0.12	1.26	0.08	2601.00	6.17E-2	6.10E-1	9.46E-3
120.00	190.00	182.50	1.26	97.70	23.52	235.62	0.27	5.00	0.08	1.02	0.05	2642.00	6.27E-2	6.22E-1	9.61E-3
130.50	200.00	192.50	1.33	100.60	21.13	223.22	0.24	4.50	0.07	0.77	0.05	2646.00	6.28E-2	6.27E-1	9.63E-3
137.00	210.00	202.50	1.40	100.00	21.60	213.63	0.24	4.20	0.07	0.71	0.04	2672.00	6.34E-2	6.31E-1	9.72E-3
144.00	220.00	212.50	1.47	101.00	20.82	212.08	0.24	4.10	0.07	0.68	0.04	2735.00	6.49E-2	6.41E-1	9.95E-3
150.83	230.00	222.50	1.53	102.70	19.55	201.81	0.22	3.90	0.06	0.65	0.04	2744.00	6.51E-2	6.50E-1	9.99E-3
156.50	240.00	232.50	1.60	104.00	18.63	190.88	0.21	3.60	0.06	0.61	0.04	3207.00	7.61E-2	7.06E-1	1.17E-2

Field Test #20
Well MW-4
06 September 1995

Time	Volume			Bromide				Hydrogen				Methane			
	Recorded	Corrected	Extr./Inj.	Conduct.	Conc.	Mass	C/Co	Meter	Conc.	Mass	C/Co	GC Area	Conc.	Mass	C/Co
minutes	*liters*	*liters*		*mV*	*mg/l*	*mg*		*%*	*mg/l*	*mg*			*mg/l*	*mg*	
164.75	250.00	242.50	1.67	104.00	18.63	186.29	0.21	3.30	0.05	0.56	0.03	2737.00	6.49E-2	7.05E-1	9.96E-3
172.33	260.00	252.50	1.74	104.10	18.56	185.95	0.21	3.10	0.05	0.52	0.03	2830.00	6.71E-2	6.60E-1	1.03E-2
179.00	270.00	262.50	1.81	104.40	18.36	184.58	0.21	3.00	0.05	0.50	0.03				
185.00	280.00	272.50	1.88	104.80	18.09	182.21	0.20	2.70	0.04	0.46	0.03			2.03E+0	
192.00	290.00	282.50	1.95	102.30	19.84	189.62	0.22	2.80	0.05	0.45	0.03	2868.00	6.80E-2		1.04E-2

Total Recovered Bromide =	9238.47	mg
Total Recovered Hydrogen =	75.80	mg
Total Recovered Methane =	15.33	mg
Extraction Flow Rate =	1.51	L/min


Hydrogen Injection in MW-4
Field Test #20, 06 September 1995
C/Co
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00
0.50
1.00
1.50
2.00
2.50
3.00
Extracted/Injected
Bromide
Hydrogen
Methane


Hydrogen Injection in MW-4
Field Test #20, 06 September 1995
C/Co
C/Co (Methane)
Extracted/Injected
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
0.0E+0
2.0E-3
4.0E-3
6.0E-3
8.0E-3
1.0E-2
1.2E-2
0.00
0.50
1.00
1.50
2.00
2.50
3.00
Bromide
Hydrogen
Methane